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EXPLORATORY STUDY OF M-1 PROPELLANT DUST EXPLOSIBILITY

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Realizing the serious potential hazards of dust particles generated when drying propellants, particularly in the new Continuous Automated Single Base Line (CASBL) facilities being erected, the Manufacturing Technology Division of ARRADCOM initiated a three-pronged attack to examine the problem.

SwRI was charged to concentrate on the explosibility of M-1 propellant dust and, through a brief cursory set of experiments, to determine the minimum energy of electrostatic discharge to induce an explosion; the minimum explosible dust

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20. concentration; and the effect of moisture, solvent, temperature and particle sizes upon the explosion threshold value of each of three M-1 propellant concentrations.

The result of this exploratory study of M-1 propellant dust explosibility was most definitive in that it demonstrated that severe flash fires and explosions can be initiated under certain sets of ambient conditions. Because of the exploratory nature of this study, it was possible only to identify the parameters which contribute to making an M-1 dust fire susceptible to an explosive reaction. Conclusions are drawn from the test program with regard to the minimum ignition energy and the minimum explosive concentrations of M-1 dust and recommendations are made for expanding this exploratory study into a more detailed evaluation.

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SUMMARY

The manufacture of M-1 propellant generates a large amount of propellant dust. The dust concentration is particularly high in the Wolverine dryers, where the freshly extruded M-1 is dried. Compounding the problem is the presence of varying amounts of water, ethyl alcohol, anhydrous ether in vapor form and dust particles. An accidental electrical spark could ignite the dust/solvent vapor laden air. If a detonation resulted, the main body of the M-1 propellant could also detonate sympathetically, allowing no time for a water deluge system, thus with disastrous results.

Realizing the serious potential hazards of dust particles generated when drying propellants, particularly in the new Continuous Automated Single Base Line (CASBL) facilities being erected, the Manufacturing Technology Division of ARRADCOM initiated a three-pronged attack to examine the problem. To gain firsthand knowledge of the qualities and characteristics of the dust generated, the Energetics Laboratory at ARRADCOM planned, and is currently carrying out, a project to collect dust from representative sites along the propellant production line at several ordnance plants. In addition, these collection activities are also being extended to the explosive drying lines at the Holston and Lone Star Ammunition Plants, wherein a variety of explosives are being manufactured.

SwRI was charged to concentrate on the explosibility of M-1 propellant dust, and, through a brief cursory set of experiments, to determine the minimum energy of electrostatic discharge to induce an explosion, the minimum explosible dust concentration, and the effect of various moisture, solvent, temperature and particle sizes have upon the explosion threshold values of each of three M-1 propellant concentrations.

The results of this exploratory study of M-1 propellant dust explosibility was most definitive in that it demonstrated that severe flash fires and explosions can indeed be initiated under certain sets of ambient conditions. Because of the exploratory nature of this study, it was possible only to identify the parameters which contribute to making an M-1 dust fire susceptible to an explosive reaction. The report begins with a general discussion of dust explosions, their causes and typical reactions, and continues with a detailed description of the test equipment and techniques used to determine the explosibility of M-1 propellant dust. Conclusions are drawn from the test program with regard to the minimum ignition energy and the minimum explosive concentrations of M-1 dust, and recommendations are made for expanding this exploratory study into a more detailed evaluation. Based on those exploratory test results, and with the conduct of the additional suggested tests, recommendations could then be made to the Army Ammunition Plants for limiting the plant exposure to potential dust explosions, to recommend venting for the dryers and operating rooms, and lastly, for the proper design of a water deluge to combat any secondary fires resulting from a dust explosion.

TABLE OF CONTENTS

TABLES

FIGURES

I. INTRODUCTION

Propellant and explosive technology has strived, over the years, to provide the most efficient safety methods for the in-process operations. This attention to increased safety and efficiency has been addressed in detail recently as part of the U.S. Army's Production Base Modernization Program under which many new explosive and propellant production facilities are being built and others are being renovated and modernized. In the interests of safety, many problem areas or techniques have been identified as severe hazard conditions and investigations were initiated to find means to reduce these hazards while maintaining minimal plant costs, and maximum plant efficiency. This report will describe the results of one such investigation.

The manufacture of M-1 propellant generates a large amount of propellant dust. The dust concentration is particularly high in the vicinity of the Wolverine dryers, where the freshly extruded M-1 is dried. Compounding the problem is the presence of varying amounts of water, ethyl alcohol, and anhydrous ether in vapor form and in the dust particles. An accidental electrical spark could ignite the dust/solvent vapor laden air. If a detonation resulted, the main body of M-1 propellant could also detonate sympathetically, allowing no time for a water deluge system, and producing disastrous results.

In general, any combustible solid when divided into minute particles and then suspended in air can explode. Such seemingly innocuous substances as starch, dusts from grain, bark, cotton, and wood, when finely divided and dispersed into the air, can become extremely dangerous [1]. One source states that the number of major dust explosions in the U. S. alone, between 1900 and 1959, excluding coal mine explosions, was 1100, in which 648 people were killed [2]. A propellant plant explosion in The Netherlands in which two people were killed has been attributed to ignition of a layer of propellant dust by static electricity [3]. As recently as December 1977, grain dust explosions in Louisiana and Texas have caused tremendous damage and loss of human life.

Realizing the serious potential hazards of drying propellant, particularly in the new Continuous Automated Single Base Line (CASBL) facility being erected, the Manufacturing Technology Division of ARRADCOM initiated a three-pronged attack to examine the problem. To gain first hand knowledge of the qualities and characteristics of the dust generated, the Energetics Laboratory at ARRADCOM is currently carrying out a project to collect dust from representative sites along the propellant production line at several ordnance plants. Typical of these is the collection from the M-1 bag loading operation at the Indiana AAP. In addition, these collection activities are also being extended to the recycle station of Composition B loaded into kettles at Milan AAP.

Using very preliminary results from these dust collection activities, ARRADCOM engaged SwRI to conduct laboratory tests. SwRI was charged to concentrate on the explosibility of M-1 propellant dust, and through a brief cursory set of experiments, to determine the following parameters:

1) Minimum energy of electrostatic discharge to induce an explosion.

2) Minimum explosible dust concentrations.

3) The effect of three different values of moisture, solvent, temperature, and particle size on the detonation threshold value of three M-1 propellant concentrations.

II. DISCUSSION OF DUST EXPLOSIONS

A general definition of dust is: A collection of finely divided solid particles. Sources that produce the largest number of dust particles are those in which solids are undergoing an energetic process such as grinding, conveying, mixing, or impacting other solid bodies in some fashion. In some of these processes, dust is the desired product while in others it is an unavoidable consequence. In any case, dust particles can be dispersed from their source in one of three ways. One is dynamic projection. It can be shown through calculations that even with tremendously high initial velocities, dust particles will travel a relatively short distance. Another mode of dispersion is diffusion, which is relatively slow. The third and primary mode of dispersion is transport by air currents. This fact is important in controlling dust levels around dust sources [4].

The increased chemical activity of dusts can be largely attributed to the greatly increased surface area per unit mass [5]. The increased surface area allows more oxygen per unit mass to be absorbed, which allows the particle to burn more rapidly when ignited. Dust behaves in some ways like a fluid, and could with reservations be termed a "discrete" fluid. Dust can be poured like a liquid, it can be compressed, and it can be "evaporated" by passing air through a body of dust [6].

There are many parameters associated with dust and dispersed dust (dust clouds). Dust parameters can be classified into two groups: those parameters which refer to individual particles and those which refer statistically to the whole dust particle population. One important parameter is particle size. But particle size cannot be specified without taking into account the shape of the particle. Many criteria have been developed for specification of particle size of irregularly shaped particles. For the purposes of this investigation particle size is determined by sieving. It is sometimes useful to determine the particle size to mass distribution of a dust sample. When dust is dispersed into the air, a useful parameter is the number of particles per unit volume, i.e., particle concentration. A more convenient and more generally used equivalent expression is dust mass per unit volume, or dust mass density. The two expressions are interchangeable if the particle size to mass distribution is known. In expressing a dust concentration, it must be realized that since a dust cloud consists of discrete solid particles, dust concentration loses meaning in the limit of small volumes. This is important to realize, for example, if the device used to ignite a dust cloud is very small, such as an electrostatic spark.

In the definition above for dust, no ranges were specified for particle size. Yet surely, there should be particle size transition

from molecular to "dust" to "ordinary" particles. One method of classification of particles by size is based on the terminal velocity at which the dispersed particles will fall back to earth. In general, the smaller the particle, the lower the terminal velocity. Therefore, in a dust cloud with a distribution of particle sizes, the mean dust particle size would decrease with time, as the larger particles would settle out first, providing no particle replenishment occurs. One group of particles is that under 1 micron(9.906×10^{-5} cm)in size, which behave like a gas when suspended in air. The terminal velocities are very low (< < 1 cm/sec) and Brownian motion masks the downward settling motion. A second group of particles lies in the range of about 1 to 120 microns (9.906×10^{-5} cm to 1.189×10^{-2} cm). The terminal velocity of those particles is fairly accurately predicted by Stokes' Law and its upper limit is about 30 cm/sec. The last group is all particles above 120 microns, with terminal velocities increasing with particle size in a complex fashion [7]. It has been reported by one source that the largest particles to actively contribute to a dust explosion were 380 microns (3.76×10^{-2} cm) in size [8]. Therefore, for the purpose of this report, reference to dust will imply particle sizes of 380 microns (3.76×10^{-2} cm) or less.

Two conditions are necessary for a dust cloud to explode. The dust concentration must lie between certain limits, and sufficient energy must be supplied to initiate the reaction. "Dust explosibility" is the relative ease with which a dust cloud will ignite and explode. Many parameters affect the explosibility of dust: concentration, particle size, air temperature, moisture content of the dust particles, and the presence of foreign particles or vapors. Most important for industrial operations is the determination of minimum ignition energy of a dust cloud and minimum explosive concentration. Minimum explosive concentrations vary from 10 to 600 mg/l [9]. It should be noted that at a concentration of 50 mg/l, the minimum explosive concentration for wheat flour is equivalent to 1 g per 0.028 m^3. Breathing air containing dust at this concentration would be difficult, and visibility would be severely limited. A good rule of thumb is that if one can see his outstretched hand, the dust concentration is probably below the minimum explosive concentration [10]. Below are listed some commonly encountered particle concentrations in mg/l ($oz/ft^3 \times 10^{-3}$) [11 and 12].

Concentration	Significance
10 - 5000	Explosive Concentration Of Dusts
.4 - .7	Dust Storm
.02 - .3	Mine Air
.008 - .03	Fog, Mist
.0002 - .007	Industrial District Air
.00007 - .0007	Rural And Suburban Air

It can thus be seen that explosive concentrations of dust are not found in most situations and are probably restricted to the immediate area around intense sources of dust particles.

Figure 1-A shows a typical ignition energy - dust concentration curve. The abcissa and ordinate axes in Figure 1 are not assigned a specific numerical scale. The purpose of the two curves is to show the relative position of values encountered in dust explosibility work. Note that in the region of minimum explosive concentration, the required ignition energy is a rapidly varying function. This fact is very important in determination of minimum ignition energy and minimum explosive concentration. Also note the transition zone, where the dust burns, but does not satisfy criteria for detonation. In Figure 1-B is shown the anticipated ignition energy - dust concentration curve for M-1 propellant dust. Note that because M-1 dust does not require oxygen, the upper explosive concentration limit should be well beyond the values (for example, 2-5 g/ℓ for coal dust) for conventional dusts. This fact suggests that propellant dusts could supply insight into the mechanisms of dust explosions. For example, one could attempt to explode the propellant in an inert atmosphere. Also, it should be noted that propellant dust in the propellant plant environment might have large quantities of ethyl alcohol and anhydrous ether with it, which would surely affect the dust explosibility.

As stated earlier, for a dust explosion to occur, there must be supplied a certain minimum ignition energy. There are many ways to introduce the necessary ignition energy into a dust cloud. One way is with an open flame. Other ways are frictional heating or sparks, intense radiation, or even shock waves from a nearby explosion. Finally, there is the electrical discharge spark. A static electrical discharge is the most likely ignition source in an M-1 plant. Minimum ignition energies in the form of electrostatic discharge are as low as five millijoules for some dusts. Some electrical spark energies and their significance are listed in Table 1. From Table 1 it can be seen that relatively small amounts of energy are required to ignite a dust cloud, and that the energy produced from a human induced spark is sufficient in magnitude.

The preceding paragraphs have provided some insight into the phenomena of dust explosions. In planning the SwRI approach to an experimental test program, a host of references were examined, two of which were deemed to be the most valuable and were used extensively throughout the test program. K. N. Palmer's book entitled Dust, Explosions and Fires [13], surveys the research that has been carried out on explosive hazards and also deals with industrial processes and preventive measures for safe handling of dust. Of greater importance

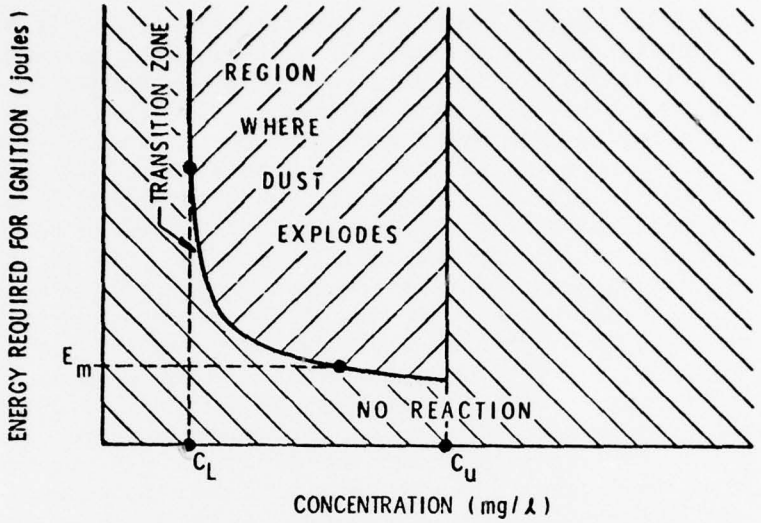

Figure 1-A. Typical Explosibility For A "Conventional" Flammable Dust

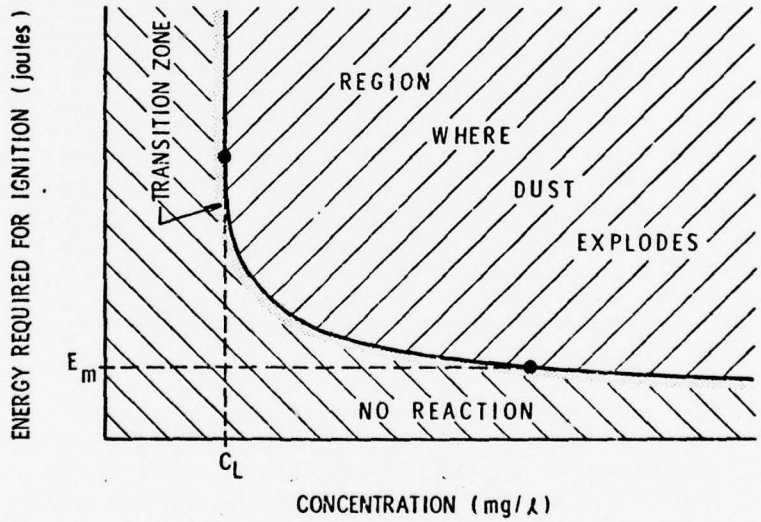

Figure 1-B. Anticipated Explosibility Curve For A Flammable Dust Not Requiring Oxygen

E_m - measured minimum ignition energy

C_L - measured minimum explosive concentration

C_u - measured upper explosive limit for "conventional" dusts due to insufficient oxygen supply

FIGURE 1. GENERALIZED DUST EXPLOSIBILITY CURVES.

TABLE 1. SOME ELECTRICAL SPARK ENERGIES AND THEIR SIGNIFICANCES

Energy (joules)*	Significance
$.13 \times 10^{-3}$	Minimum ignition energy for some flammable vapors
5×10^{-3}	Minimum ignition energy for some dust clouds
7×10^{-3}	Lead azide ignites
.01	Minimum ignition energy for propellant dust layer (Netherland report 150 microns)
.013	Minimum ignition energy for M-1 dust layer (Radford)
$5\text{-}18 \times 10^{-3}$	Energy in static electricity spark produced by human
.15	Minimum ignition energy for M-1 dust cloud - SwRI
.25	Produces a heavy shock in humans
7.2	Threshold for producing ventricular fibrillation in humans
10.0	A human is in danger of death
11.03	Composition B ignites
12.5	Black Power ignites
$5 \times 10^{8} - 10^{10}$	Lightning bolt

References [2, 14, 15, 16, 17, 18]

*To obtain energy in ft-lbs, multiply energy in joules by 0.74.

is the Bureau of Mines Report No. 5624 [19] which details the accepted procedures for the use of the Hartmann Apparatus for determining the minimum energies and minimum dust concentrations which could result in a potentially explosive situation. The Bureau of Mines procedures for determining dust explosibility were followed as closely as possible in the research program to be described in Section III of this report. The detailed results of the test program are discussed in Section IV.

Two Appendices are included with the report, Appendix A gives the results of 146 experimental tests in complete detail. Appendix B relates the attempts to find more accurate flame propagation criteria based upon the analysis of pressure-time curve traces which were taken during many of the experimental test firings.

III. EQUIPMENT AND TECHNIQUES TO DETERMINE DUST EXPLOSIBILITY

The purpose of this testing program was to conduct a preliminary investigation into the effects of certain propellant dust parameters on minimum explosive concentration and minimum ignition energy: dust particle size, air temperature, moisture content, and introduction of solvent into the propellant dust. This section of the report will describe the equipment and experimental techniques used in the performance of the test evaluation program. It should be noted here and it will be restated throughout the report that procedures used by the Bureau of Mines were studied and used when feasible.

M-1 Propellant Dust Production

It was noted earlier that a parallel investigation being conducted by ARRADCOM was concerned with collecting typical dust samples at the operating ammunition plants. Since these dust collections had not yet begun, it was deemed necessary for the experimental program to grind M-1 propellant grains to the suitable particle sizes for explosibility investigations. For the tests to be conducted which are described in this report, the dust was obtained from single-perforated M-1 propellant grains.

A grain of propellant measures 0.1143 cm in diameter x 0.49 cm long, and has a single 0.032 cm diameter hole in the center. The bulk density is approximately 625 kg/m^3. M-1 propellant contains 84.2 percent nitrocellulose (13.15 percent N), 9.9 percent dinitrotoluene, 4.9 percent dibutylthalate, and 1 percent diphenylamine.

In the manufacture of M-1 propellant, large amounts of M-1 dust particles are produced during the drying process, possibly in explosive concentrations. Compounding the problem is the presence of ethyl alcohol and ether vapors evaporating from the M-1 propellant, and the dust particles in the propellant plant can vary greatly in moisture, solvent content, and size. Therefore to exactly simulate the dust environment in a propellant plant would be most difficult; hence, the test procedures should be designed in a way that the contribution of each parameter to dust explosibility can be discerned. The information gained about each parameter can then be combined to assess the explosibility situation in the total propellant plant environment.

The production of M-1 dust in the laboratory was made difficult by two properties of M-1. First, M-1 is highly flammable and could possibly be ignited by sparks or excessive shock. Most grinding procedures utilize shock or friction to produce dust. This meant that a

tradeoff between grinding efficiency and possibility of ignition had to be made. Secondly, the M-1 pellets would tend to split along the longitudinal axis, and the long fibers generated were too flexible to grind into small particles. Initially, attempts were made to grind the propellant using a mortar and pestle. After failing with mortar and pestle, a Wiley ball mill tumbler was used to grind the propellant. Needed for the use of the ball mill is water and ice which act both as a lubricant and also serve to extinguish possible fires. After three days of tumbling, the M-1 had been ground to a point where approximately one-third to one-fifth of the propellant load would pass through a Tyler No. 150 mesh sieve, i.e., two-thirds or four-fifths of the dust particles were larger in size than 105 microns (1.04×10^{-2} cm). Succeeding attempts to grind M-1 propellant in the ball mill were unsuccessful in duplicating the dust size distribution. Hence, the procedure was abandoned.

The next grinding attempt utilized a paint shaker. Two capsules containing approximately 50 gr. each of M-1 and water and suitably sized ceramic balls were agitated on a paint shaker for approximately 20 minutes. The resultant wet propellant particles were dried under a heat lamp and sieved to obtain size-to-sample mass distribution which is shown in Table 2-A. Also, the sieve mesh sizes are shown in Table 2-B.

It was pointed out in Section II that particle sizes between 1 and 120 microns closely followed Stokes' Law and that these would be the most likely dust particle sizes to be found in an ammunition plant drying operation. Therefore, it was decided that the test program would be conducted using two particle sizes from the grinding operation: dust caught between No. 140 and No. 200 sieves (dust particles between 75 and 105 microns) and dust passing through the No. 200 sieve (75 microns). Note that 1 micron is equal to 9.906×10^{-5} cm.

Two dust moisture contents were also tested. These two dust moisture types were termed "wet" and "dry". "Wet" dust is dust that had not been placed in a desiccator, with an average moisture content by weight of about 3 percent. "Dry" dust is dust that was placed in a desiccator, with a moisture level approaching 0 percent.

To produce dust particles that contained solvent (either ethyl alcohol or anhydrous ether), a quantity of solvent was added to a weighed quantity of "dry" propellant dust. This "solvent wet" propellant dust was dried until it weighed 10 percent more than its dry weight. It was then stored in air tight containers prior to testing. Immediately before testing, the solvent wet propellant was sieved to break up the adhering particles, allowing more solvent to escape, lowering the solvent content below 10 percent by an unknown amount.

TABLE 2-A. PROPELLANT PARTICLE SIZE MASS DISTRIBUTION.

Grinding Tests Of M-1 SP Propellant

		Percent	
Start	135.8 g	of 132.91	
Above No.50 Sieve	123.57	92.97	
No.70	6.32	4.76	
No.140	1.26	0.95	Batch A Paint Shaker
No.200	0.41	0.31	
Through No.200	1.15	0.87	
	132.91 g	99.86%	

		Percent	
Start	278.46 g	of 276.41	
Above No.50 Sieve	240.40	86.97	
No.70	20.42	7.39	
No.150	6.10	2.21	Batch B Paint Shaker
No.200	2.00	0.72	
Through No.200	7.49	2.71	
	276.41 g	100.00%	

TABLE 2-B.

Listing of Sieve And Particle Sizes

U.S. STANDARD SIEVE SERIES	TYLER SCREEN SCALE EQUIV.	OPENING (Microns)
No. 50	48 Mesh	297
No. 70	65 Mesh	210
No. 140	150 Mesh	105
No. 200	200 Mesh	75

1 micron = 9.906×10^{-5} cm.

Ignition Source

Since the Bureau of Mines [19] has a standardized test program and equipment for dust explosibility tests, SwRI implemented these standards into the test program. A Hartmann Apparatus was used for the explosibility tests. The ignition source was an electrical discharge spark, produced by an apparatus consisting of a 100/400 v power supply, luminous tube transformer, and a capacitor bank. The capacitance of the capacitor bank could be varied in 1 microfarad increments, allowing the stored electrical energy to be varied. The voltage applied to the capacitors was either 100 or 400 volts, depending on the energy level desired. The capacitors, upon being charged by a power supply, would be disconnected from the power supply and discharged into the luminous tube transformer. The high voltage output from the transformer is passed through an air gap in the test chamber where ignition of the dust occurs. The energy of the spark in the test chamber is calculated as $1/2\ CV^2$ where C is capacitance of the capacitor bank and V is voltage across the capacitor bank. It is realized that this value is somewhat high, due to losses in the transformer and that some energy remains in the capacitor bank. Thus the calculated value of energy is a relative, not absolute value [19]. The use of the electrical discharge system required timing between production of the dust cloud and release of the electrical spark. To understand this delay, the Hartmann Apparatus needs to be described.

The Hartmann Apparatus

One of the greatest difficulties in dust explosibility tests is production and maintaining a uniform dust cloud. In testing, it is desirable to have as small a dust cloud as possible to avoid dangerous, powerful explosions. Yet confining a dust cloud to a small volume poses some problems. The dispersed dust particles will tend to rapidly adhere to the sides of the container. Also, since the dust particles fall at a rate dependent on size, the particles must either be replenished, or the dust cloud must be ignited before the concentration has decreased from particles falling or adhering to the container walls. There are some devices which through a metering out of dust particles attempt to replenish those lost from the dust cloud. The Hartmann Apparatus, on the other hand, produces a momentary dust cloud from a blast of air which passes through a dust sample. After a short period of turbulence, a momentarily uniform dust cloud is produced at which time an attempt should be made to ignite the dispersed dust. The Hartmann Apparatus was used in all of the M-1 dust explosibility tests.

The principal components of the Hartmann Apparatus (see Figures 2, 3, 4) consist of a 30.5 cm, vertically mounted lucite tube and the dispersion cup to which the lucite tube attaches. The combined volume of the lucite tube and the dispersion cup (i.e., the

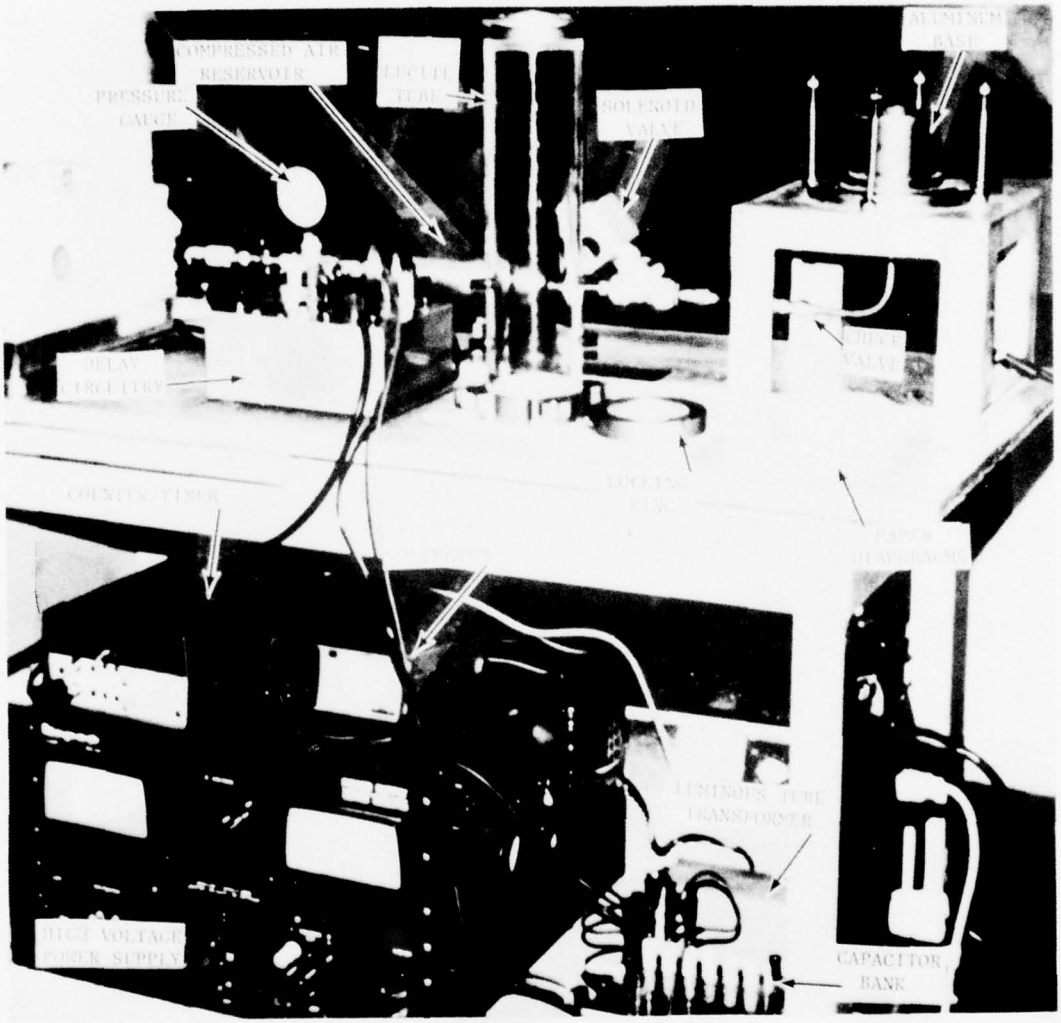

FIGURE 2. VIEW OF ENTIRE TEST APPARATUS INCLUDING HARTMANN APPARATUS AND ELECTRONICS.

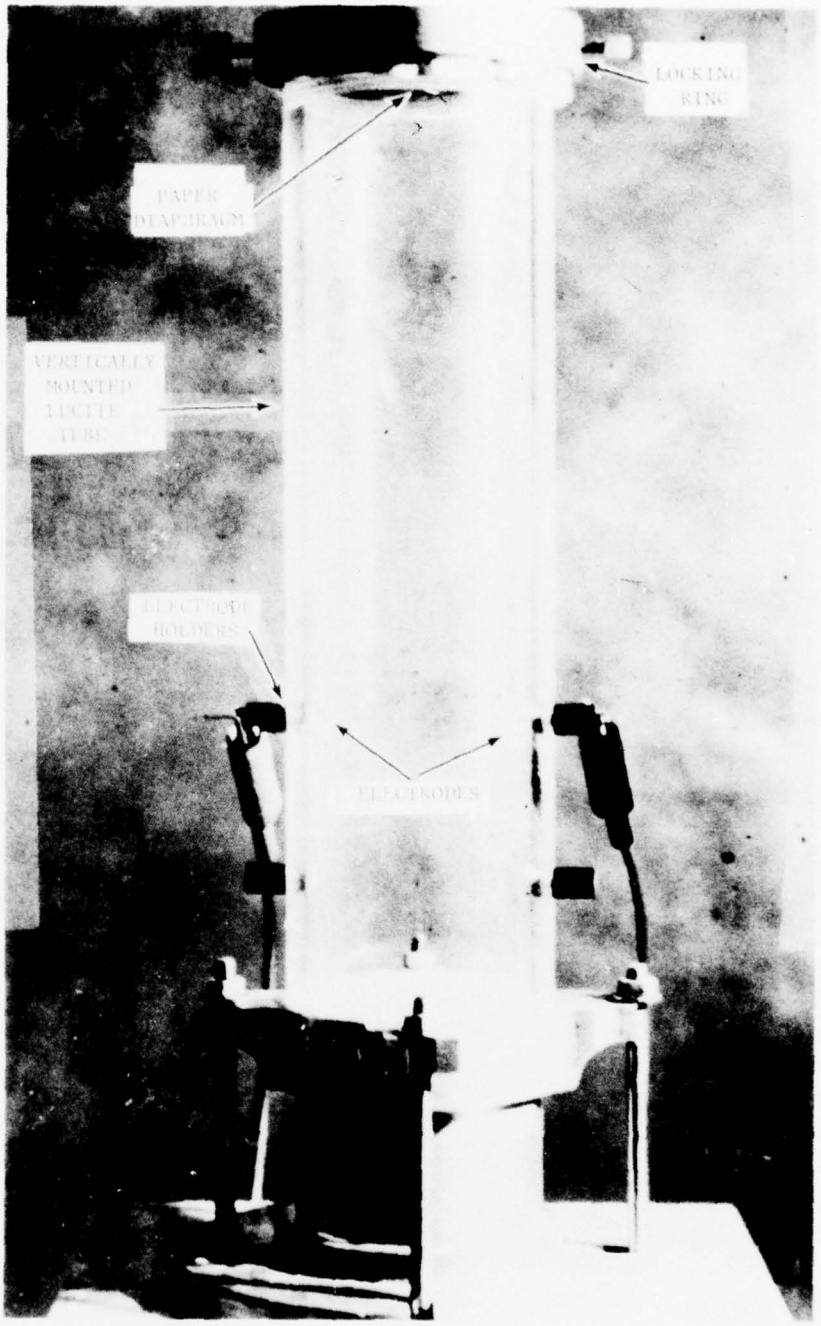

FIGURE 3. CLOSEUP VIEW OF HARTMANN APPARATUS

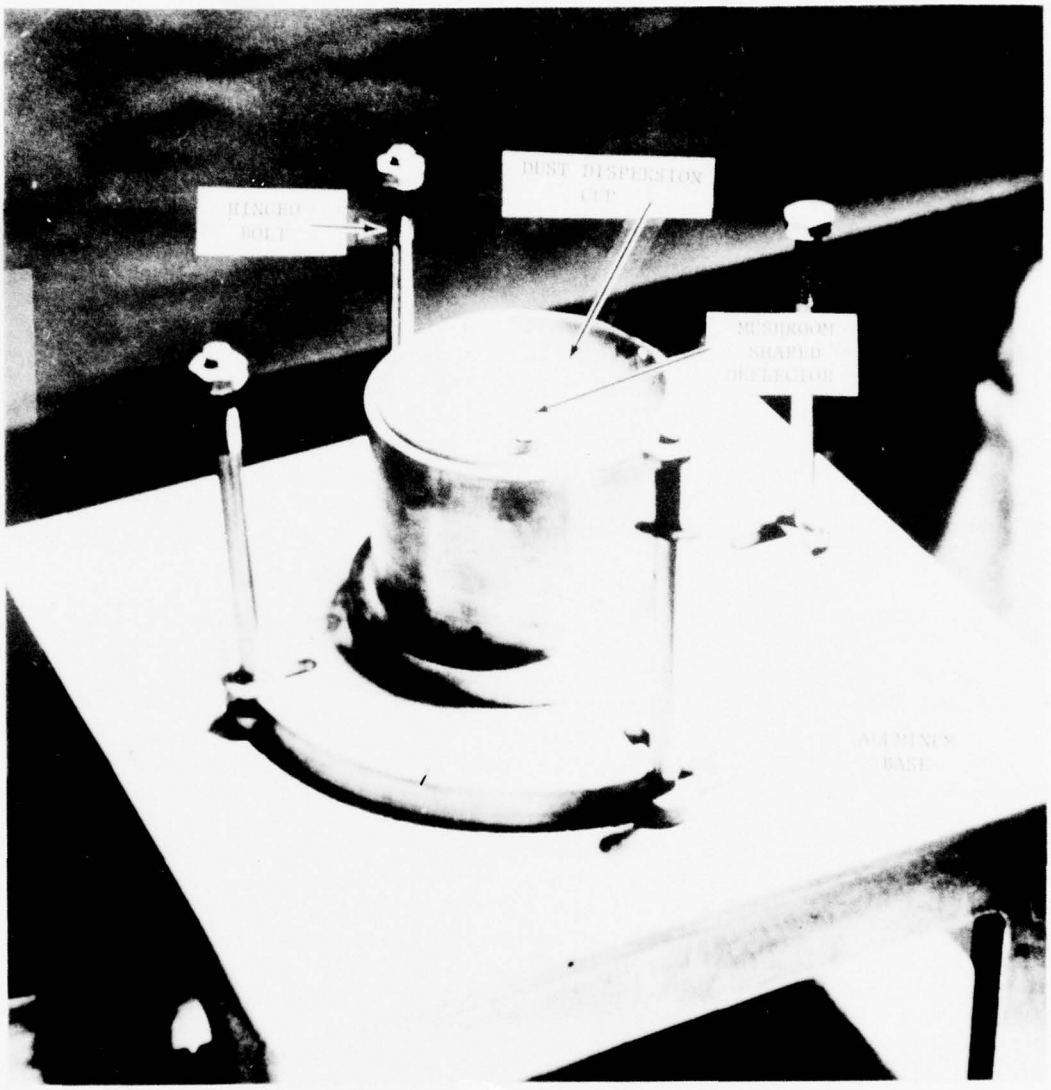

FIGURE 4. THE DUST DISPERSION CUP OF THE HARTMANN APPARATUS.

assumed volume of the dust cloud) is 1.23 liters. This is the combustion chamber for the dust. Components can be divided into two groups: the dust dispersion elements and the ignition elements. A weighed amount of dust is placed in the dispersion cup around a mushroom shaped deflector in the bottom of the dispersion cup. The deflector serves two purposes: it deflects the incoming air so as to disperse the dust sample, and it regulates the rate at which air can flow from the compressed air reservoir into the lucite tube. The compressed air reservoir, with a volume of 1.31 liters, is used to produce a blast of air to disperse the dust lying in the bottom of the dispersion cup. The pressure used in the reservoir can be between (5 and 15 psi) 3.4×10^4 to 10.3×10^4 pascals, however, 6.8×10^4 pascals was used for all tests conducted. The compressed air in the reservoir is released by means of a solenoid valve, and a check valve is located between the solenoid valve and the dispersion cup. Its purpose is to prevent any flow of combustion gases back into the solenoid valve or reservoir.

Supporting all the components listed so far is the aluminium base. The lucite tube can be rapidly attached to the dispersion cup for a test or detached for cleaning and reloading with dust by means of the hinged bolts. At the top of the lucite tube is placed a paper diaphragm, held in place by the locking ring. The paper diaphragm confines the dispersed dust particles within the tube before ignition, yet allows incoming air from the reservoir to escape. The diaphragm will burst if the burning dust produces a pressure of at least (535.8 psi) 2.1×10^5 pascals .

The ignition elements consist of two groups (two electrodes per group) of 20 gauge tungsten electrodes and electrode holders. The upper group, 10.2 cm above the bottom of the lucite tube, with a gap of .32 cm, was used in all tests conducted.

After the blast of air from the reservoir, a certain period of time must pass for the dust concentration to become fairly uniform in the test chamber, before attempting to ignite the dust cloud. Also, if too much time should elapse, the dust will settle out on the walls and bottom of the lucite tube. It can be seen that delay timing between release of the compressed air and the discharge of the capacitors is essential. This timing was accomplished electronically. Upon initiating the solenoid valve by pushing a button, a timing sequence is initiated which will trigger the capacitors to discharge into the luminous tube transformer at a later instant. This delay time was varied until an optimum value was found, i.e., one that occurred when the dust cloud was most uniform. For all tests conducted, about a 1/2 second time delay was used. This time delay for each was measured. Figure 5 is a block diagram of the electronic instruments used.

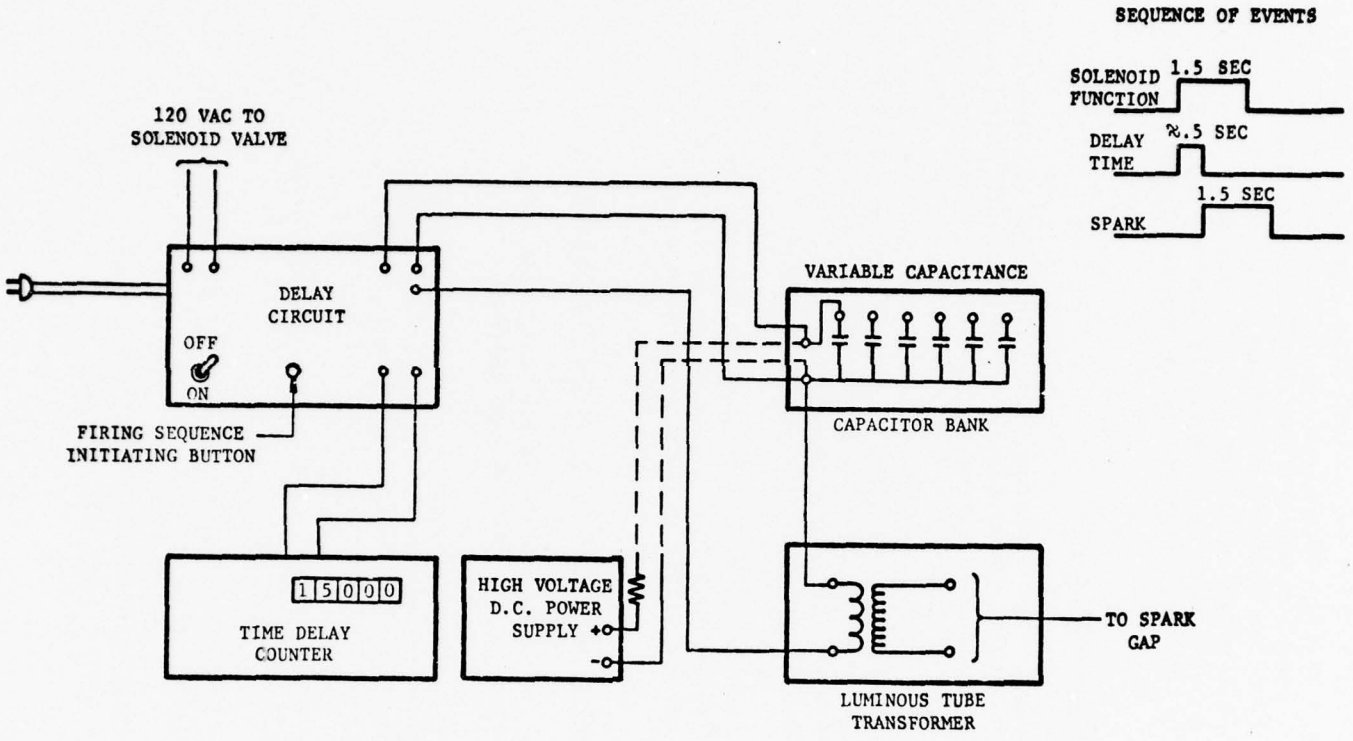

FIGURE 5. Electronics System Diagram

In summary, the production of uniform dust clouds is difficult. An approximation to a uniform dust cloud can be made with the Hartmann Apparatus, which was used for the M-1 dust explosibility tests. It should be realized that the Hartmann Apparatus will allow an accurate determination of relative explosibility of different dusts, but that the data obtained cannot always be directly applied to real life situations because of the empirical nature of the testing apparatus [19].

Flame Propagation Determination

The dispersed dust, upon ignition, would burn with varying intensities, ranging from no visible reaction to detonation with rupture of the paper diaphragm. An immediate problem visualized was: What should be used as criteria for propagation of flame in the dust cloud. It was decided that the same propagation criteria would be used as those of the Bureau of Mines in Report 5624 [19]. A summary of the most important points stated by the Bureau of Mines Report 5624 in the use of the Hartmann Apparatus for determination of Minimum Explosive Concentration and Minimum Ignition Energy is as follows:

All tests were conducted with dust samples through the No. 200 sieve (less than 75 microns) and with a moisture content less than 5 percent. A dust sample is placed in a desiccator to achieve the low moisture level.

A. Determination Of Minimum Explosive Concentration

1. Mass of dust placed in Hartmann Apparatus should be varied in 5 milligram increments.

2. The spark gap should be .5 cm. Tests should be made with the electrodes placed 5 cm and then 10.1 cm from the bottom of the lucite tube.

3. The spark should be a continuous induction spark of 23.5 milliamperes.

4. The reservoir air pressure should be varied until an optimum value is found.

5. Propagation of flame has occured only if rupture of the paper diaphragm occurred.

If the diaphragm ruptures, the dust amount is decreased by 5 mg and the testing continues until there is no diaphragm rupture in four successive trials for a given weight of dust. The lowest weight at which the diaphragm bursts is used to calculate the minimum explosive concentration. Tests should be made with the electrodes 5 cm and then 10.2 cm from the bottom of the tube. The average of the two weights thus obtained (one at 5.08 cm and one at 10.2 cm) is divided by the volume of reaction chamber for the value of the minimum concentration.

B. Determination Of Minimum Ignition Energy

1. Mass of dust placed in the Hartmann Apparatus should be kept constant at a level corresponding to 5 to 10 times the minimum explosive concentration.

2. The spark gap width should be varied to find an optimum value.

3. The spark should be obtained from a single capacitative discharge. The capacitors discharge through a luminous-tube transformer.

4. The reservoir air pressure should be varied until an optimum value is found.

5. A 10.2 cm flame is considered propagation of flame. Tests are repeated at a given energy level until propagation occurs, or four tests have been conducted. If propagation occurs, the ignition energy is lowered by decreasing the capacitance by 1 microfarad (if energy is less than 50 millijoules, and four if above) and up to four tests are tried at this new ignition energy. This process is repeated until no propagation occurs in four trials. The lowest energy at which propagation occurs is the minimum ignition energy.

Note how only a 10.2cm flame is considered propagation for minimum ignition energy tests, and a ruptured diaphragm is required for propagation in the minimum explosive concentration tests. Also note how factors inherent to the test apparatus itself (spark gap, suspension pressure, delay time) are made constant by choosing optimized values, i.e., values which would most likely encourage ignition. Again it should be realized that the values obtained with the Hartmann Apparatus may be

different from those obtained in a real life situation. However, the Hartmann Apparatus will accurately determine the explosibility of one dust sample relative to another [19]. It can be argued that visual determination of propagation is not the best method, therefore, possibility of using pressure-time traces as a supplement to the propagation criteria is considered in Appendix B.

Photographic Coverage of Tests

Representative tests were photographed with a high speed camera at 64 frames per second. Both tests in which propagation occurred and tests in which no reactions occurred were photographed. The films show clearly that the dust samples were fully dispersed and relatively uniform at the moment ignition was attempted. See Figures 6-10 in Section IV.

IV. DISCUSSION OF TEST EVALUATIONS

Establishing a Test Matrix

In the manufacture of M-1 propellant, a large amount of propellant dust is produced. An especially critical operation is the drying of freshly extruded M-1. "Wet" M-1 contains water, ethyl alcohol, and anhydrous ether, the latter two extremely flammable. The drying process creates propellant dust with varying amounts of solvents in the dust particles, and disperses solvent vapors in the air, potentially a hazardous situation. In an addendum to an existing contract, SwRI was to determine the minimum ignition energy in the form of an electrostatic discharge for M-1 dust in relation to five parameters each at three different values: dust concentration, moisture content, air temperature, particle size and solvent content. It was seen that a test matrix of 3^5 or 243 test parameter combinations were possible without considering spark energy variations. The number of combinations could be reduced by the use of fractional factorial design. The advantages of a fractional design are that the important parameters and their combinations are identified without the need for a time consuming probe of the full matrix, and testing of unimportant parameter combinations is minimized. In this fashion, it is possible to isolate subregions of the full matrix where strong functional relationships exist, which can be explored in more detail, if warranted. Functional factorial design is based on statistics, and a discussion of the technique is contained in Davies' book [20].

In the initial experimental design, the full matrix of 3^5 parameter combinations was reduced by a factor of 1/3 to 81 combinations. At this level, all main effects and all two-factor interactions are clear of one another, i.e., they are not confounded. Higher order interactions are assumed to be negligible. All of the parameter combinations in this 1/3 fractional matrix are shown in Table 3 where the superscripts 0, 1 and 2 represent low, medium and high levels of concentrations (C), temperature (T), particle size (P), moisture (M), and solvent (S). The three values initially decided upon for each parameter are:

C (dust particle concentrations)- 50, 250, and 500 mg/l

T (air temperatures)- 24, 38 and 52° C

P (particle sizes)- particles ≤ 75 microns, particles ≥ 105 microns, and particles ≤ 210 microns

TABLE 3. FRACTIONAL TEST MATRIX

1.	$C^0T^0P^0M^0S^0$	28.	$C^1T^0P^1M^0S^1$	55.	$C^0T^2P^1M^1S^2$
2.	$C^1T^2P^0M^0S^0$	29.	$C^1T^0P^1M^1S^0$	56.	$C^2T^1P^0M^1S^2$
3.	$C^1T^0P^2M^0S^0$	30.	$C^1T^0P^0M^1S^1$	57.	$C^1T^2P^1M^2S^0$
4.	$C^1T^0P^0M^2S^0$	31.	$C^0T^1P^0M^1S^1$	58.	$C^1T^2P^1M^0S^2$
5.	$C^1T^0P^0M^0S^2$	32.	$C^2T^2P^2M^0S^0$	59.	$C^1T^0P^2M^1S^2$
6.	$C^0T^1P^2M^0S^0$	33.	$C^2T^2P^0M^2S^0$	60.	$C^0T^1P^2M^1S^2$
7.	$C^0T^1P^0M^2S^0$	34.	$C^2T^2P^0M^0S^2$	61.	$C^1T^2P^0M^1S^2$
8.	$C^0T^1P^0M^0S^2$	35.	$C^0T^2P^2M^2S^0$	62.	$C^1T^2P^2M^1S^0$
9.	$C^0T^0P^1M^2S^0$	36.	$C^0T^2P^2M^0S^2$	63.	$C^1T^2P^2M^0S^1$
10.	$C^0T^0P^1M^0S^2$	37.	$C^0T^0P^2M^2S^2$	64.	$C^1T^0P^2M^2S^1$
11.	$C^0T^0P^0M^1S^2$	38.	$C^2T^0P^2M^0S^2$	65.	$C^0T^1P^2M^2S^1$
12.	$C^2T^1P^0M^0S^0$	39.	$C^2T^0P^2M^2S^0$	66.	$C^1T^2P^0M^2S^1$
13.	$C^2T^0P^1M^0S^0$	40.	$C^2T^0P^0M^2S^2$	67.	$C^1T^1P^2M^2S^0$
14.	$C^2T^0P^0M^1S^0$	41.	$C^0T^2P^0M^2S^2$	68.	$C^1T^1P^2M^0S^2$
15.	$C^2T^0P^0M^0S^1$	42.	$C^2T^2P^1M^1S^0$	69.	$C^1T^0P^1M^2S^2$
16.	$C^0T^2P^1M^0S^0$	43.	$C^2T^2P^1M^0S^1$	70.	$C^0T^1P^1M^2S^2$
17.	$C^0T^2P^0M^1S^0$	44.	$C^2T^0P^2M^1S^1$	71.	$C^1T^1P^0M^2S^2$
18.	$C^0T^2P^0M^0S^1$	45.	$C^0T^2P^2M^1S^1$	72.	$C^2T^1P^1M^1S^1$
19.	$C^0T^0P^2M^1S^0$	46.	$C^2T^2P^0M^1S^1$	73.	$C^1T^2P^1M^1S^1$
20.	$C^0T^0P^2M^0S^1$	47.	$C^2T^1P^2M^1S^0$	74.	$C^1T^1P^2M^1S^1$
21.	$C^0T^0P^0M^2S^1$	48.	$C^2T^1P^2M^0S^1$	75.	$C^1T^1P^1M^2S^1$
22.	$C^1T^1P^1M^0S^0$	49.	$C^2T^0P^1M^2S^1$	76.	$C^1T^1P^1M^1S^2$
23.	$C^1T^1P^0M^1S^0$	50.	$C^0T^2P^1M^2S^1$	77.	$C^2T^2P^2M^2S^1$
24.	$C^1T^1P^0M^0S^1$	51.	$C^2T^1P^0M^2S^1$	78.	$C^2T^1P^2M^2S^2$
25.	$C^0T^1P^1M^1S^0$	52.	$C^2T^1P^1M^2S^0$	79.	$C^1T^2P^2M^2S^2$
26.	$C^0T^1P^1M^0S^1$	53.	$C^2T^1P^1M^0S^2$	80.	$C^2T^2P^1M^2S^2$
27.	$C^0T^0P^1M^1S^1$	54.	$C^2T^0P^1M^1S^2$	81.	$C^2T^2P^2M^1S^2$

M (moisture content by weight) - 0, 5, and 10 percent

S (solvent content by weight) - 0 percent, 10 percent ethyl alcohol, 10 percent anhydrous ether

It was decided that each of the 81 parameter combinations would be tested at three different energy values: .5, 2.0 and 8.0 joules. This made a total of 81 times 3 or 243 tests. It was realized at this time the test program above was too large to carry out within the imposed limits of time and funds. Further reduction of the test program was necessary.

The test matrix was revised after studying literature on Bureau of Mines procedures in dust explosibility testing [19, 21]. It is helpful to examine the Bureau of Mines explosibility testing procedure. A frequently mentioned, yet not very well defined term is "dust explosibility". For this paper dust explosibility will be defined as the ease with which a dust cloud can be caused to produce an explosion. Dust explosibility is difficult to define quantitatively because of its dependence on many parameters, and because explosion criteria are themselves inexact. To have meaning, there must be a way to relate the explosibility between different dusts (say, for example, flour and coal dust). The Bureau of Mines has developed a quantitative expression for dust explosibility, the Index of Explosibility, in which the explosibility of a certain dust sample is compared to a standard dust sample, i.e., Pittsburg coal dust. An analogy is found in relating the explosive power of various explosives to that of TNT (TNT Equivalency Tests). All explosibility tests are conducted with dust through the No. 200 sieve (particles $\leq$ 75 microns) and with a moisture content less than 5 percent. The Index of Explosibility is computed as shown below:

$$\text{Index of Explosibility} = \text{Ignition Sensitivity} \times \text{Explosion Severity}$$

where

$$\text{Ignition sensitivity} = \frac{\text{Ignition Temp.} \times \text{Minimum Ignition Energy}}{\text{Ignition Temp.} \times \text{Minimum Ignition Energy}}$$

$$\times \frac{\text{Minimum Explosive Concentration [Pittsburgh Coal Dust]}}{\text{Minimum Explosive Concentration [Dust Sample]}}$$

and

$$\text{Expl. Severity} = \frac{\text{Max. Expl. Pres.} \times \text{Max. Rate Of Pres. Rise [Dust Sample]}}{\text{Max. Expl. Pres.} \times \text{Max. Rate Of Pres. Rise [Pittsburgh Coal Dust]}}$$

For all three dimensionless quantities defined above, a value greater than one indicates increased danger over coal dust while a value less than one indicates a decreased danger relative to coal dust. All three quantities are calculated from specific test results: minimum ignition energy, minimum ignition temperature, minimum explosive concentration and explosion pressure-time traces.

The result of the Bureau of Mines procedure is information relating dust samples having standarized parameters of particle size and humidity through comparison with Pittsburg coal dust. Furthermore, these dust parameters and procedures of testing are chosen such that the explosion probability is maximized and functional dependence on the parameters is constant in the region of the values of the parameters.

The test program initially to be conducted by SwRI can be seen to be only a portion of the Bureau of Mines dust explosibility testing process. It was seen that a compromise had to be made between obtaining the functional relationship between the dust parameters in relation to explosibility over a range of values (originally three values) and the probing over a very small range with a large number of repetitive tests to comply with the Bureau of Mines procedures for determination of minimum ignition energy and minimum explosive concentrations. Furthermore, it was seen that for a propellant plant the most useful test data would be minimum ignition energy and minimum explosive concentration as found by Bureau of Mines procedures in relation to the parameters of particle size, solvent content, and moisture content.

A test program was chosen which represented a three way compromise between the original Scope of Work, the procedures used by the Bureau of Mines and limitations of time, money, dust supply, and equipment availability. For the test program it was decided that the test matrix would contain the effects of three parameters in relation to minimum explosive concentration and minimum ignition energy. The three parameters are propellant dust particle size, moisture content of the dust, and the addition of solvent to the propellant dust. Two dust particle sizes were used: particles 75 microns (through No. 200 mesh sieve) and particles in the size range of 75-105 microns (dust particles caught between the No. 140 mesh and the No. 200 mesh sieves). Two moisture contents were used: 0 percent moisture content by weight (dust was placed in a desiccator) and approximately a 3 percent moisture content by weight (dust not placed in a desiccator). Three solvent variations were used: the addition of no solvent, addition of 10 percent ethyl alcohol by weight, and the addition of 10 percent anhydrous ether by weight.

The parameters listed above can be combined into a 3 x 2 x 2 test matrix. Only seven of the twelve test cases were used in the test program. This is without considering ignition energy or dust concentration values.

The testing program conducted differed from the Bureau of Mines procedure in four major aspects. For determining minimum explosive concentration, a single capacitative discharge was passed through a luminous tube transformer rather than a continuous induction spark. It can be argued that the use of a single timed spark can be as effective as a continuous discharge, providing that a proper delay time is used and the spark has sufficient energy. Also, minimum explosive concentration tests were conducted using electrodes placed 10.2cm above the bottom of the lucite tube, and not at both a 10.2 cm height and then a 5.08cm height as specified. A third difference is the use of 5 milligram increments in determining minimum explosive concentration and 1 to 4 microfarad increments to vary energy for minimum explosive concentration and 1 to 4 microfarad increments to vary energy for minimum ignition energy determination. Finally, the four-trial verification procedures were not followed. The reason for the last three differences is the large number of tests which would be required.

To determine minimum explosive concentration and minimum ignition energy for one test case would require about 100 tests, or 1200 tests for the whole program, if the Bureau of Mines procedure is followed exactly. Realizing that this number of tests could not be conducted within the imposed limits of time, budget, or propellant dust supply, only selected tests were fired from each test case. For purposes of an exploratory set of tests, this procedure would give some estimate of minimum explosive concentration and minimum ignition energy.

Results of Test Program

To open our discussion of the test results and to better understand the operation of the Hartmann Apparatus, reference is made to Figures 6 through 10. Here, through a series of high speed motion picture frames, the dispersion of the dust cloud in the test chamber can be clearly seen. From selected frames, an attempt is made to illustrate first, the early stage of M-1 dust rising in the test chamber (Figure 6), then, the rising of dispersion of the cloud (Figures 7-9), and finally the occurrence of an explosion wherein the paper diaphragm at the top of the test chamber is ruptured (Figure 10).

In Appendix A the detailed data for all 146 tests are tabulated. In the table the following are listed: Date, Test No., Mass of

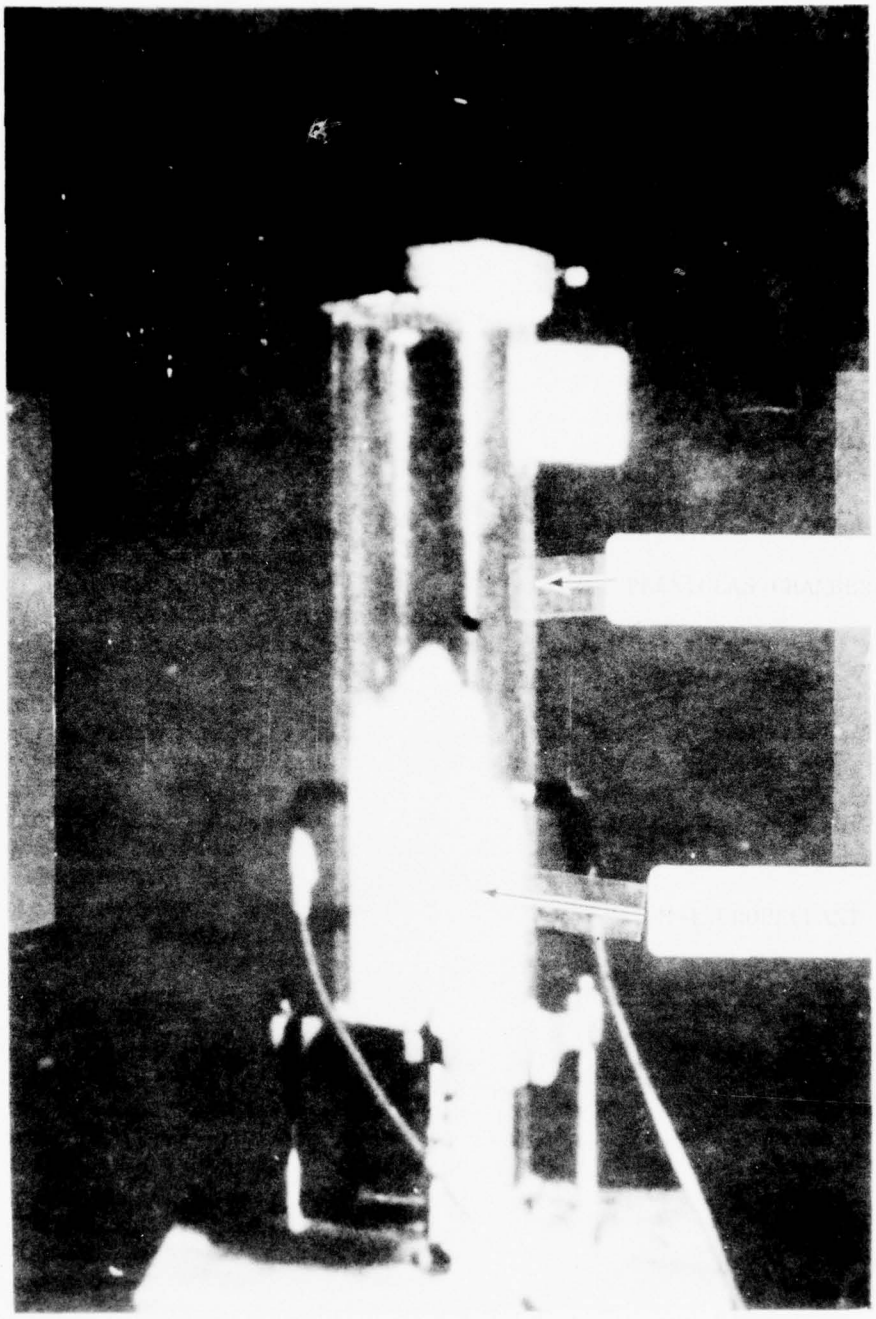

FIGURE 6. EARLY STAGE OF M-1 DUST RISING IN TEST CHAMBER.

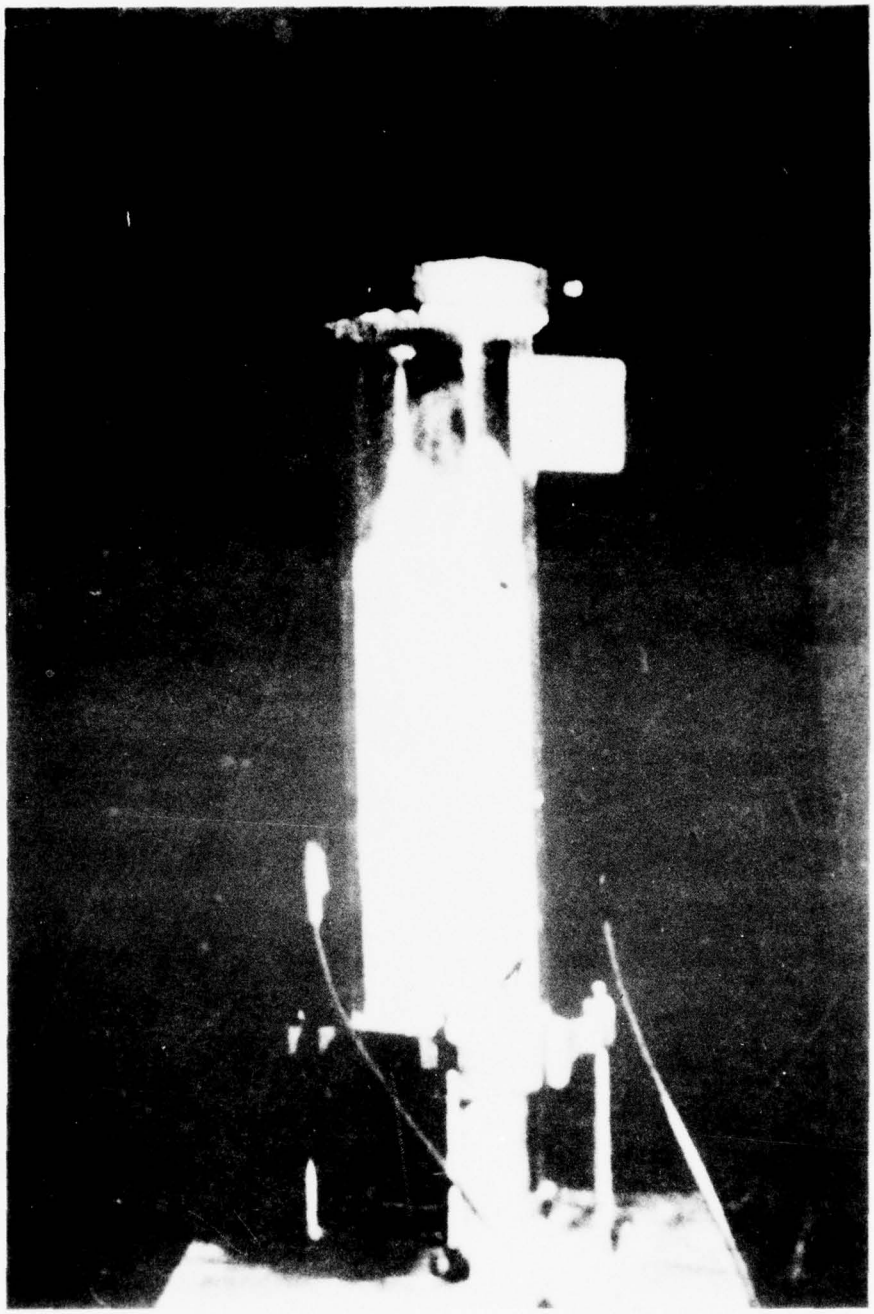

FIGURE 7. M-1 DUST RISING IN CHAMBER, 0.1 SEC AFTER RELEASE.

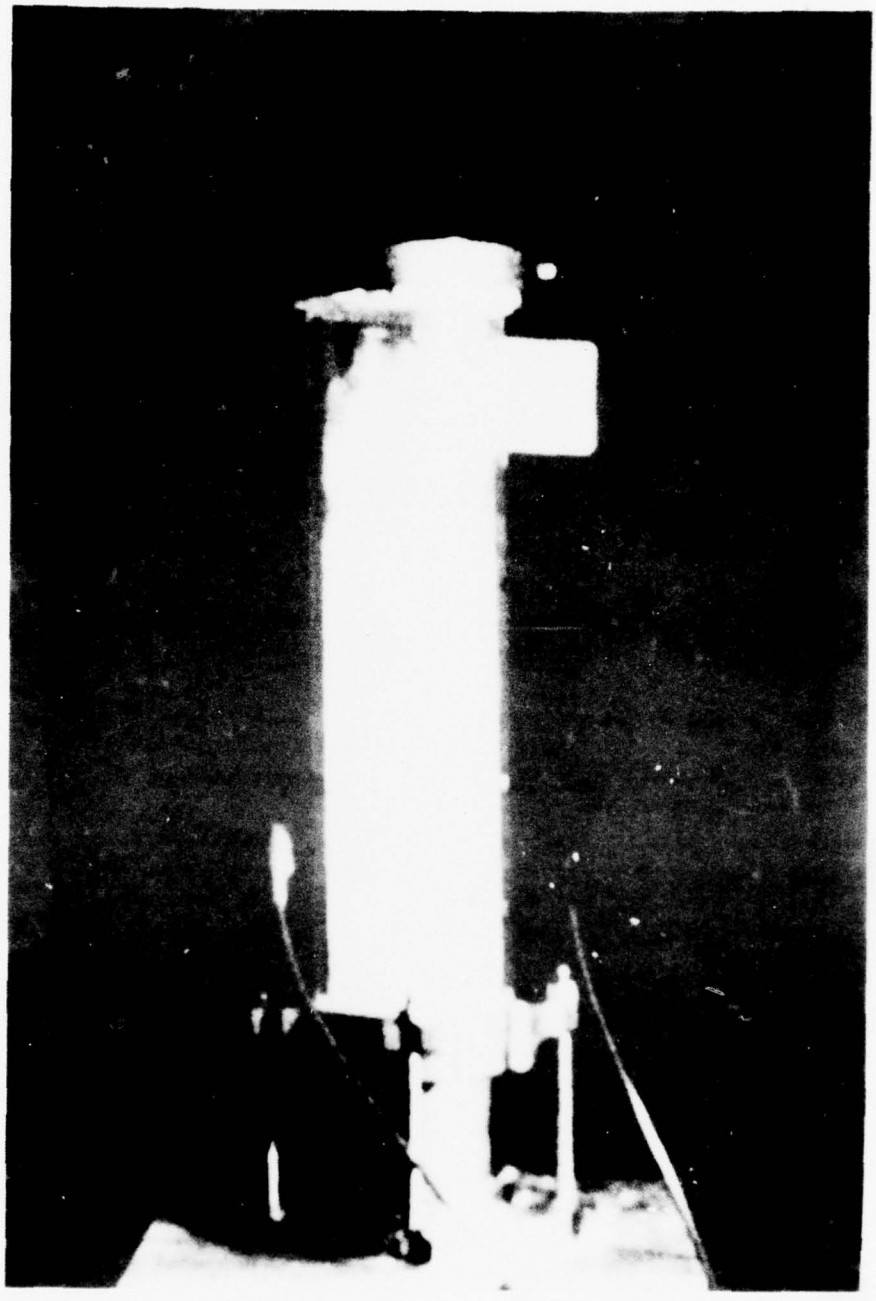

FIGURE 8. M-1 DUST RISING IN CHAMBER, 0.2 SEC AFTER RELEASE.

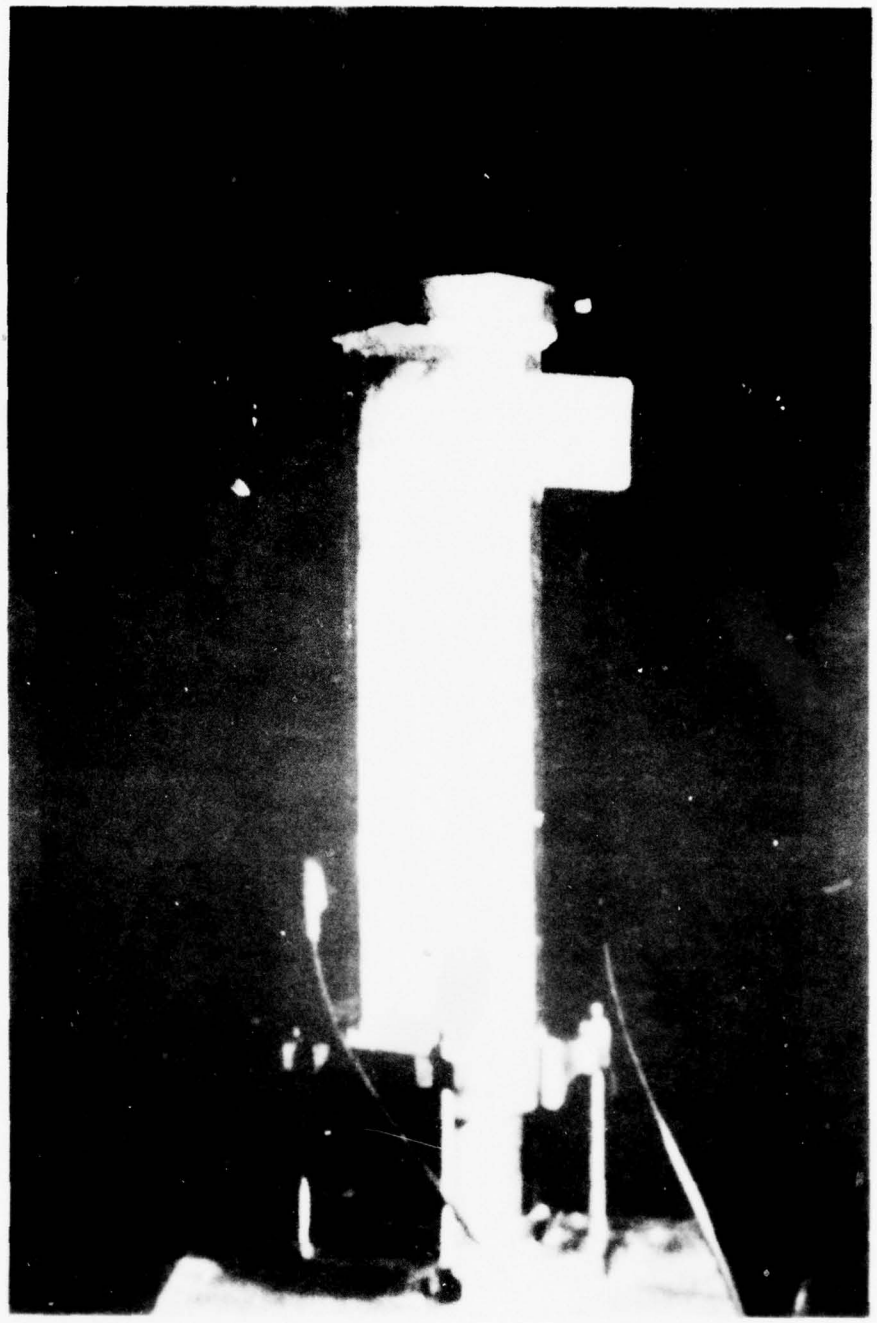

FIGURE 9. M-1 DUST DISPERSED IN CHAMBER JUST PRIOR TO SPARK IGNITION (0.5 SEC).

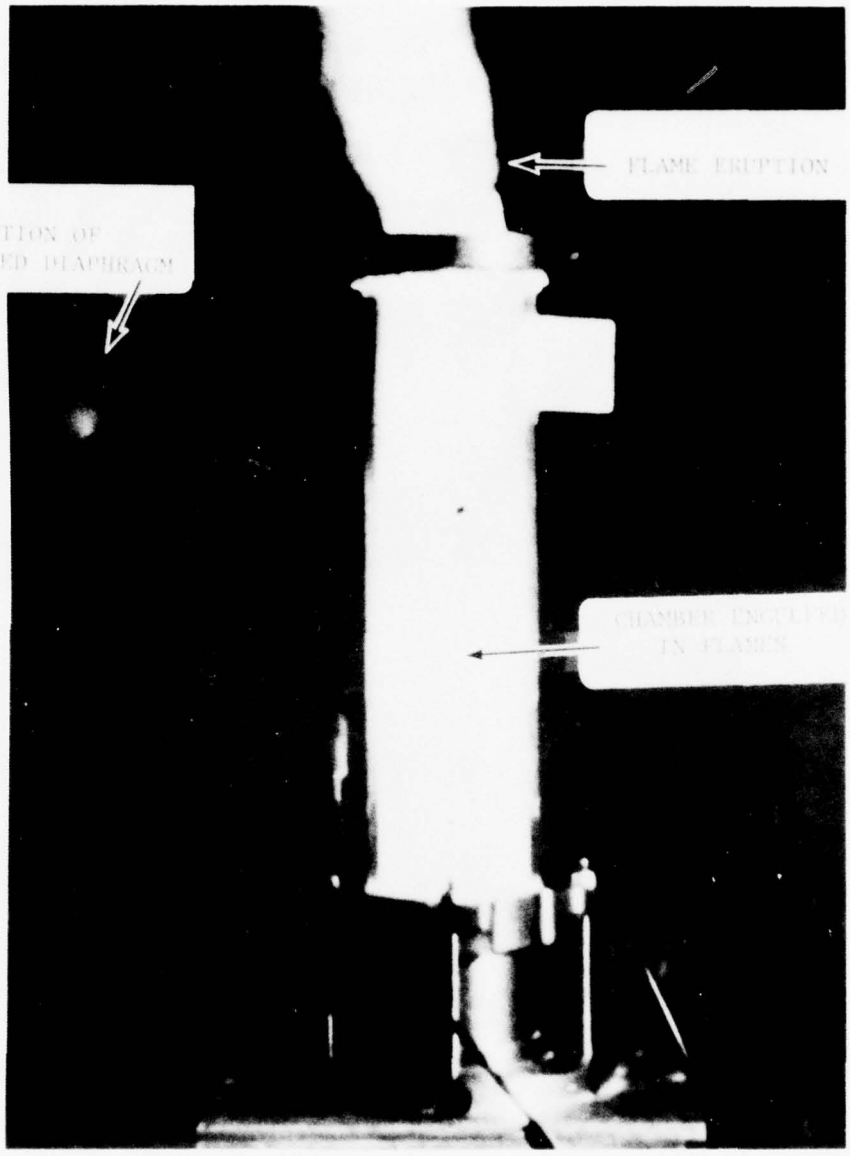

FIGURE 10. EXPLOSION OF DUST, RUPTURE OF DIAPHRAGM, AND FLAME ERUPTION, 0.1 SEC, AFTER SPARK IGNITION.

Propellant (mg) placed in the Hartmann Apparatus, size of screen through which particles were sieved, moisture or solvent content in percent by weight, the type of solvent used, the air temperature in degrees centigrade, the delay time between release of compressed air and spark in milliseconds, the spark gap in centimeters, the suspension pressure in pascals, capacitance of capacitor bank in microfarads, the voltage across the capacitor bank in volts, the stored energy in the capacitor bank (equal to $1/2\ CV^2$) and the test results. For purposes of our discussion, the significant data of the test program for the seven test cases are broken out in Tables 4-10. In the tables are listed: Test No., the concentration of the dispersed dust in milligrams per liter, the ignition energy in joules and the test results. Also, the tables divide the data into two categories:

1. Data concerning minimum ignition energy, and

2. Data concerning minimum explosive concentrations.

Note that some tests appear in both categories; their values of energy and dust concentration make this possible.

Referring to Table 4, it can be seen that the minimum ignition energy for dry M-1 dust $\leq$ 75 microns ($\leq 7.62 \times 10^{-3}$ cm) in size is $\leq$ 0.15 joules. The minimum explosive concentration lies between 203 mg/l and 244 mg/l. Referring to Table 5, the minimum ignition energy for dry M-1 dust, 75-105 microns (7.62×10^{-3} to 10.2×10^{-3} cm) in size is $\leq$ 0.175 ($\leq$ 0.13 ft-lbs) joules. The minimum explosive concentration lies between 122 and 244 mg/l. Note that for Test Cases III - VII shown in Tables 6-10, the highest dust concentration tested was 366 mg/l. Table 6 lists the data for wet M-1 propellant dust, 75-105 microns in size, at 3 percent moisture content. The minimum explosive concentration is apparently above 366 mg/l, but there are insufficient data for determination of minimum ignition energy.

Tables 7-10 all involve dust with solvent introduced. The data from Tables 7-10 can be discussed together because the results are the same for each test case. Note that no propagation occurred in any of the tests used in the last four test cases. It was expected that the addition of solvent to the dust would lower the minimum ignition energy. This, however, was not observed. (Compare Tables 4-6 with Tables 7-10.)

In using propagation criteria, it was found from tests that usually the dust cloud either reacted in the most severe manner (burst the diaphragm with an accompanying "bang") or had a minimal reaction (small localized flame around the spark gap). There were few tests

TABLE 4. TEST CASE I DATA*

Propellant Size: ≤75 microns
Moisture Content: 0% by weight (propellant placed in desiccator)
Solvent: None added

Test No.	Propellant Concentration (mg/l) †	Ignition Energy (j)	Result ‡
	Minimum Ignition Energy		
2	488	0.5	+
3	488	0.375	+
4	488	0.30	+
5	488	0.25	+
6	488	0.20	+
7	488	0.15	-
8	488	0.15	+
9	488	0.15	-
	Minimum Explosive Concentration		
2	488	0.5	+
41	244	0.5	+
33	203	8.0	-
28	163	8.0	-
23	122	8.0	-

Conclusion: Minimum ignition energy ≤0.15 joules and minimum explosive concentration lies between 203 and 244 mg/ℓ.

* Air reservoir pressure in all test cases was 68 kPa. Spark gap width was .318 cm. Delay time between air reservoir release and spark discharge was about 0.5 sec in all test cases.

† The mass of the propellant placed into the Hartmann Apparatus was divided by 1.23 liters, the volume of the Hartmann Apparatus, to obtain concentration of the dispersed dust.

‡ For minimum ignition energy tests, (+) denotes ignition of dust while (-) denotes failure to ignite. Similarly for minimum explosive concentration tests, (+) indicates that an explosion occurred while (-) indicates failure to do so. Criteria for determination of (+) or (-) were the same as those listed in Bureau of Mines Report No. 5624. These criteria have been previously described in this report.

TABLE 4. TEST CASE I DATA* (cont'd)

Conversion factors to use in Tables 4-10 are:

1 micron = 9.906×10^{-5} cm

1 mg/ℓ = 1×10^{-3} oz/ft^3

1 joule = .74 ft-lbs

TABLE 5. TEST CASE II DATA

Propellant Size: 75-105 microns
Moisture Content: 0% by weight (propellant placed in desiccator)
Solvent: None added

Minimum Ignition Energy

Test No.	Propellant Concentration (mg/l)	Ignition Energy (j)	Result
49	488	0.50	+
50	488	0.45	+
51	488	0.40	+
52	488	0.35	+
53	488	0.30	+
54	488	0.25	+
56	488	0.225	+
55	488	0.20	-
66	366	0.175	+
65	366	0.15	-

Minimum Explosive Concentration

49	488	0.50	+
63	366	0.25	+
57	244	0.30	+
62	122	8.00	-

Conclusion: Minimum ignition energy $\leq$ 0.175 joules and minimum explosive concentration lies between 122 and 244 mg/ℓ.

TABLE 6. TEST CASE III DATA

Propellant Size: 75-105 microns
Moisture Content: Up to 3 percent by weight (propellant not placed in desiccator)
Solvent: None added

Minimum Explosive Concentration

Test No.	Propellant Concentration (mg/1)	Ignition Energy (j)	Result
71	366	8.0	-
70	244	8.0	-
69	163	8.0	-
68	122	8.0	-

Conclusion: Minimum dust concentration is above 366 mg/ℓ.

TABLE 7. TEST CASE IV DATA

Propellant Size: 75-105 microns
Moisture Content: 0 percent (propellant placed in desiccator)
Solvent: Propellant consisted of 10 percent ethyl alcohol by weight

Minimum Ignition Energy

Test No.	Propellant Concentration (mg/l)	Ignition Energy (j)	Result
79	366	8.0	-
78	366	2.0	-

Minimum Explosive Concentration

79	366	8.0	-
77	244	8.0	-
74	122	8.0	-

Conclusion: Insufficient data for conclusions.

TABLE 8. TEST CASE V DATA

Propellant Size: ≤ 75 microns
Moisture Content: 0 percent (propellant placed in desiccator)
Solvent: Propellant consisted of 10 percent ethyl alcohol by weight

Minimum Ignition Energy

Test No.	Propellant Concentration (mg/l)	Ignition Energy (j)	Result
92	366	2.0	-

Minimum Explosive Concentration

92	366	2.0	-
91	244	8.0	-
82	122	8.0	-

Conclusions: Insufficient data for conclusions.

TABLE 9. TEST CASE VI DATA

Propellant Size: 75-105 microns
Moisture Content: 0 percent by weight (propellant placed in desiccator)
Solvent: Propellant consisted of 10 percent anhydrous ether by weight

Minimum Ignition Energy

Test No.	Propellant Concentration (mg/l)	Ignition Energy (j)	Result
100	366	8.0	-
99	366	2.0	-

Minimum Explosive Concentration

100	366	8.0	-
98	244	8.0	-
95	122	8.0	-

Conclusions: Insufficient data for conclusions.

TABLE 10. TEST CASE VII DATA

Propellant Size: ≤ 75 microns
Moisture Content: 0 percent by weight (propellant placed in desiccator)
Solvent: Propellant consisted of 10 percent anhydrous ether by weight

Minimum Ignition Energy

Test No.	Propellant Concentration (mg/l)	Ignition Energy (j)	Result
107	366	2.0	-
108	366	8.0	-

Minimum Explosive Concentration

108	366	8.0	-
106	244	8.0	-
103	122	8.0	-

Conclusions: Insufficient data for conclusions.

where propagation criteria were satisfied without diaphragm rupture. There are several questions, i.e., problems that arose during the course of the testing program which should be mentioned, as they may have already occurred to the reader. One involves the question of applicability of the test results to real life situation. It is believed however, that the optimum conditions created in the Hartmann Apparatus reflect the most dangerous situation possible for a given dust sample. A problem was encountered in the repeatability of tests. It was found that tests could not always be repeated from day to day. Also, there is the question of the effects of the addition and subsequent evaporation of water or solvent on M-1 propellant. The effect on explosibility is unknown. Finally, there is a question on the true particle size of the dust cloud in the Hartmann Apparatus. The dust particle sizes are known because they pass through a given sieve size. But the particles are then allowed to come in contact and adhere to each other. A certain amount of energy is needed to break apart these adhering particles and it is doubtful that it is fully accomplished in the Hartmann Apparatus. The method used in the tests was to sieve the dust immediately before the test in hope of breaking apart the adhering particles.

Both K. N. Palmer [13] and the Bureau of Mines [19] address these questions. Nevertheless, the Bureau of Mines procedure is the most used and respected technique and with recognition of the above mentioned problems can provide some important data to be used by those in dust explosion prevention work. In Figures 11 and 12 are shown the explosibility curves for dry M-1 dust (<75 microns and also 75 to 105 microns in size). For both Figures 11 and 12, ignition energy is plotted as a function of dust concentration. In Figure 11, a large number of data points are plotted to show the transition between no reaction and an explosion. The data points termed "localized reaction" and "burning" are cases of minimal or threshold reaction, and would be termed "no reaction", using Bureau of Mines criteria. In Figure 12 the Bureau of Mines criteria are strictly adhered to, hence the apparent "sharp" transition between no reaction and explosion.

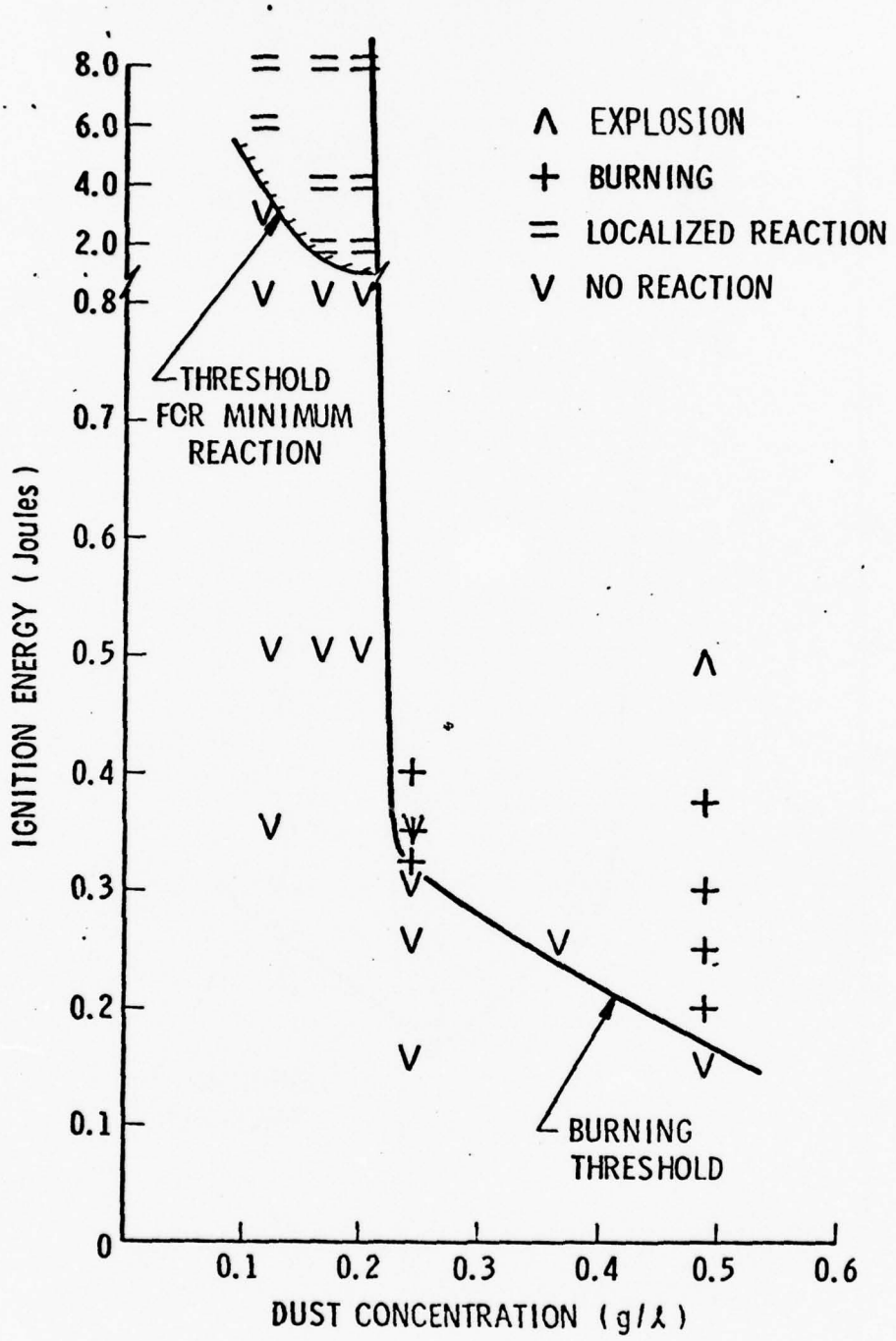

FIGURE 11. Dry M-1 Propellant Dust Explosibility (Thru No. 200 Sieve, ≤75 **Microns)**

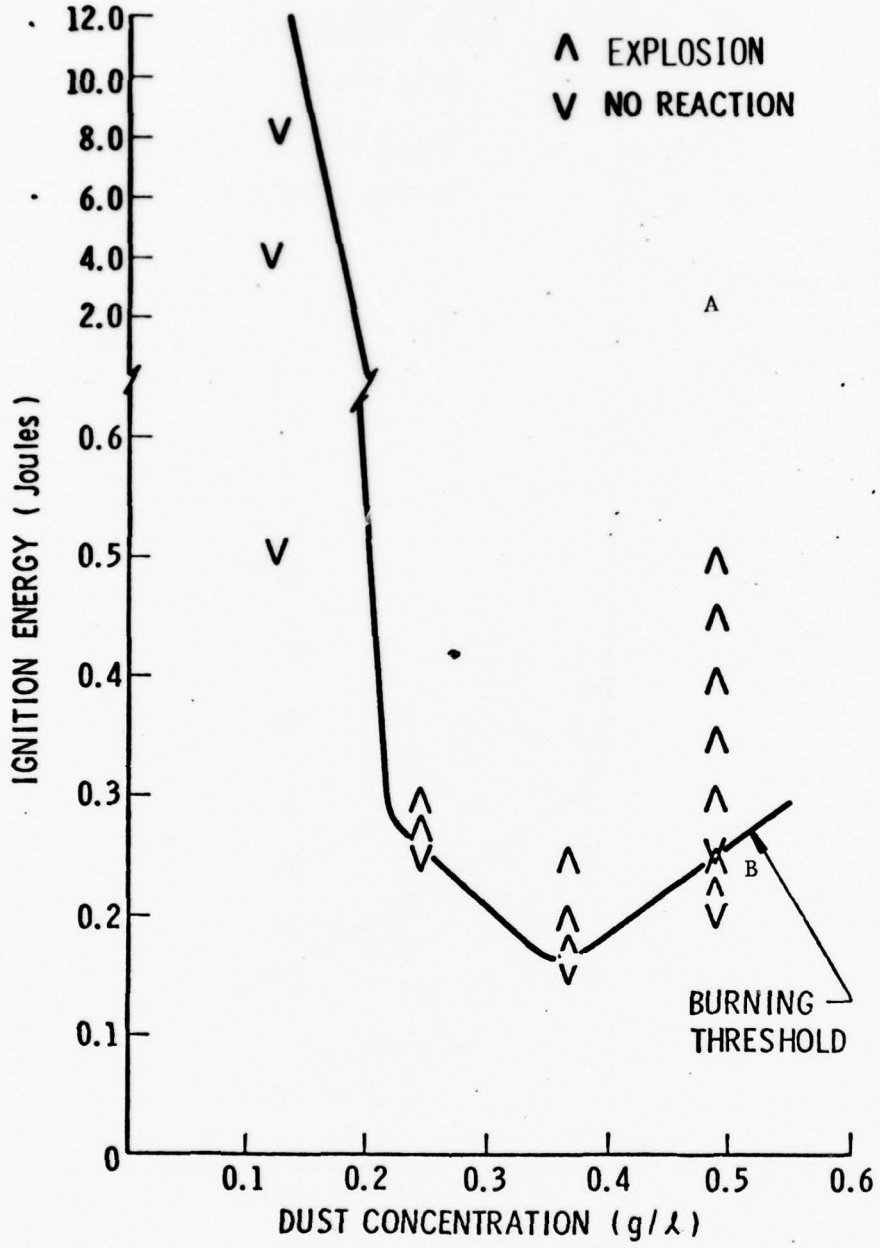

FIGURE 12. Dry M-1 Propellant Dust Explosibility
(Particle Size Between 75 and 105 Microns)

V. CONCLUSIONS

1. Explosibility of M-1 dust appears to increase with a decrease in particle size.

2. Explosibility of M-1 dust appears to decrease with addition of moisture to dust.

3. Particles $\leq$ 75 microns in size have a minimum ignition energy of approximately 0.15 joules, and the minimum explosive concentration lies between 203 and 244 milligrams per liter.

4. Larger M-1 dust particles between 75 and 105 microns have a minimum ignition energy of approximately 0.175 joules, and the minimum explosive concentration lies between 122 and 244 milligrams per liter.

5. These values are more than an order of magnitude lower concentration than the explosive concentrations of the non-oxidizing coal dust at 2,000 mg/ℓ.

VI. RECOMMENDATIONS

The exploratory study of M-1 propellant dust explosibility was most definitive in that it demonstrated that severe flash fires and explosions can indeed be initiated under certain sets of ambient conditions. Because of the exploratory nature of this study, it was possible only to identify the pertinent parameters which contribute to making an M-1 dust cloud susceptible to an explosive reaction. It was not possible to explore, in detail, each of the quantitative values of these contributing parameters, however it was possible to arrive at specific recommendations for future investigations as follows:

1. Dust samples collected from the actual operations of the Army Ammunition Plants should be used in the experiments. There is reason to believe that laboratory ground M-1 propellant does not produce representative dust specimens for true evaluation.

2. A means should be developed for the introduction of solvent vapors into the test chamber in such quantities that they will represent the ambient environment at select points in the production plant.

3. The total test matrix suggested by the Bureau of Mines should be tested to include the two solvents of interest, several moisture contents, and several particle sizes.

4. If the total Bureau of Mines test matrix for each of the above parameters is too large, at least a complete run of the Bureau of Mines matrix should be made to determine the minimum dust concentration levels and minimum ignition energies for the most realistic set of test parameters. These latter parameters would be determined following a survey of the ammunition plants and the collection of particles at the plant sites.

5. During the conduct of the above mentioned tests, a determination should be made of the severity of the pressure rise within the test chamber. These measurements would be made through the use of pressure transducers mounted within the test chamber and the data obtained would be correlated with the results of the burst diaphragm of the Hartmann Apparatus.

6. Through the conduct and successful conclusion of the suggested tests, recommendations could then be made to the Army Ammunition Plants for:

a) limiting the plant exposure to potential dust explosions,

b) recommending adequate venting for the dryers and for the operating rooms such that minor explosions and minor pressure rises would not result in catastrophic destruction, and

c) recommendations made for the proper design of a water deluge to combat any secondary fires that might occur as a result of a flash fire within the dust environment.

7. As a concluding recommendation, a program should be initiated (encompassing a reasonable period of time) to investigate better techniques of determining minimum dust explosive concentrations and minimum energy requirements. The Hartman Apparatus suffers in that it cannot maintain a constant dynamic environment. Several research teams in Europe have studied these problems extensively. New techniques are evolving which show great promise of offering the capability of more controlled experiments and more accurate data. These advances should be considered for application to ammunition plant dust problems where dust explosions could have catastrophic repercussions.

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APPENDIX A

Test Data

USEFUL CONVERSION UNITS FOR APPENDIX A TEST DATA

2.54 cm = 1 in.

3.5×10^{-5} oz. = 1 mg

.74 ft-lbs = 1 joule

6.89×10^{3} pascals = 1 psi

APPENDIX A. TEST DATA.

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time (ms)	Spark Gap (cm)	Suspensi Pres.kP
8/19/77	1	600	200	dry	-	27.5	518	.318	68.9
8/19/77	2	600	200	dry	-	27.5	508	.318	68.9
8/19/77	3	600	200	dry	-	29.0	510	.318	68.9
8/19/77	4	600	200	dry	-	29.0	511	.318	68.9
8/19/77	5	600	200	dry	-	29.5	510	.318	68.9
8/19/77	6	600	200	dry	-	30.0	508	.318	68.9
8/19/77	7	600	200	dry	-	31.0	511	.318	68.9
8/19/77	8	600	200	dry	-	31.0	511	.318	68.9
8/19/77	9	600	200	dry	-	31.0	507	.318	68.9
8/20/77	10	300	200	dry	-	36.0	511	.318	68.9
8/20/77	11	300	200	dry	-	36.0	508	.318	68.9
8/22/77	12	300	200	dry	-	31.5	506	.318	68.9
8/22/77	13	300	200	dry	-	35.0	509	.318	68.9
8/22/77	14	300	200	dry	-	35.5	510	.318	68.9
8/22/77	15	300	200	dry	-	36.0	510	.318	68.9
8/23/77	16	150	200	dry	-	31.0	503	.318	68.9
8/23/77	17	150	200	dry	-	32.5	507	.318	68.9
8/23/77	18	150	200	dry	-	34.5	505	.318	68.9
8/23/77	19	150	200	dry	-	36.0	508	.318	68.9
8/23/77	20	150	200	dry	-	37.0	506	.318	68.9
8/24/77	21	150	200	dry	-	31.0	505	.318	68.9
8/24/77	22	150	200	dry	-	32.5	507	.318	68.9
8/24/77	23	150	200	dry	-	33.0	506	.318	68.9
8/24/77	24	200	200	dry	-	33.5	507	.318	68.9
8/24/77	25	200	200	dry	-	33.5	505	.318	68.9
8/24/77	26	200	200	dry	-	34.5	507	.318	68.9

Capacitance (uf)	Voltage (v)	Energy (J)	Result
50	100	0.25	No flame observed (m-1)
100	100	0.50	Loud detonation
75	100	0.375	Tube full of fire for 0.5 sec
60	100	0.30	Tube full of fire for 0.5 sec
50	100	0.25	Slightly less than #3 & 4, but still a good flame
40	100	0.20	Burned w/more intensity than #5
30	100	0.15	No flame
30	100	0.15	Burned well - not too intense
30	100	0.15	No flame
30	100	0.15	Spark at gap - no flame at all
50	100	0.25	Spark at gap - no flame at all
70	100	0.35	30% propellent burned, tube partially filled w/flame
80	100	0.40	30% propellent burned, tube partially filled w/flame
60	100	0.30	No flame
65	100	0.325	30% propellent burned, tube partially filled w/flame
70	100	0.35	Spark at gap - no flame at all
100	100	0.50	Spark at gap - no flame at all
10	400	0.80	Spark at gap - no flame at all
14	400	1.12	Spark at gap - brief 1.27 cm flame
20	400	1.60	Spark at gap - no flame
30	400	2.40	Spark at gap - no flame
75	400	6.00	Spark at gap - small 1.27 cm lateral flame along electrode
100	400	8.00	Spark at gap - small 1.27 cm lateral flame along electrode
100	100	0.50	Spark at gap - no flame
14	400	0.12	Spark at gap - no flame
25	400	2.00	Spark at gap - small 1.27 cm lateral flame along electrode

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time ms	Spark Gap (cm)	Suspens Pres.
8/24/77	27	200	200	dry	-	35.0	507	.318	68.9
8/24/77	28	200	200	dry	-	35.0	505	.318	68.9
8/25/77	29	250	200	dry	-	30.5	504	.318	68.9
8/25/77	30	250	200	dry	-	31.0	507	.318	68.9
8/25/77	31	250	200	dry	-	31.5	504	.318	68.9
8/25/77	32	250	200	dry	-	31.5	506	.318	68.9
8/25/77	33	250	200	dry	-	33.5	498	.318	68 9
8/25/77	34	450	200	dry	-	34.0	502	.318	68.9
8/26/77	35	450	200	dry	-	30.5	501	.318	68.9
8/26/77	36	150	200	dry	-	31.5	501	.318	68.9
8/26/77	37	200	200	dry	-	33.5	498	.318	68.9
8/26/77	38	200	200	dry	-	33.5	499	.318	68.9
8/26/77	39	200	200	dry	-	34.0	502	.318	68.9
8/31/77	40	300	200	dry	-	30.0	515	.318	68.9
8/31/77	41	300	200	-	-	30.0	501	.318	68.9
8/31/77	42	300	200	-	-	30.0	502	.318	68.9
8/31/77	43	300	200	-	-	30.5	503	.318	68.9
9/1/77	44	300	200	dry	-	24.0	498	.318	32.7
9/1/77	45	300	200	dry	-	24.5	500	.318	32.7
9/1/77	46	300	200	dry	-	27.5	502	.318	68.9
9/1/77	47	600	200	dry	-	27.5	502	.318	68.9
9/1/77	48	600	150			28.0	502	.318	68.9

ion	Capacitance (uf)	Voltage (v)	Energy (J)	Result
	50	400	4.00	Spark at gap - small 1.27cm lateral flame along electrode
	100	400	8.00	Spark at gap - small 1.27cm lateral flame along electrode
	100	100	0.50	Spark at gap - no flame
	14	400	1.12	Spark at gap - small 1.27cm lateral flame along electrode
	25	400	2.00	Spark at gap - small 1.27cm lateral flame along electrode
	50	400	4.00	Spark at gap - small 1.27cm lateral flame along electrode
	100	400	8.00	Spark at gap - small, slightly more intense flame along electrode
	50	100	0.25	Spark at gap - no flame
	100	100	0.50	Spark at gap - no flame - residual resv. pres. 34.5 kPa
	100	400	8.00	Spark at gap - small 1.27cm lateral flame along electrode - Before Test #36 check valve was adjusted for "0" gauge pres. w/o rupture diaphram. After test - 13.8 kPa residual resv. pres. w/diaphram.
	25	400	2.00	Spark at gap - small 1.27cm lateral flame along electrode
	50	400	4.00	Spark at gap - small 1.27cm lateral flame along electrode - slightly more
	100	400	8.00	Spark at gap - small 1.27cm lateral flame along electrode - about same as above
	70	100	0.35	Spark at gap - no flame at all
	100	100	0.50	Detonation? - filter paper dia. rupt. - no flame
	80	100	0.40	Spark at gap - no flame
	90	100	0.45	Spark at gap - no flame
	80	100	0.40	Detonation? - diaphram rupture - no flame
	60	100	0.30	Detonation? - diaphram rupture - no flame
	100	100	0.50	Spark at gap - no flame
	75	100	0.375	Detonation? - diaphram rupture - no flame
	50	100	0.25	Spark at gap - no flame

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time mS)	Spark Gap (cm)	Suspens Pres.kP
9/2/77	49	600	150	dry	-	24.5	497	.318	68.9
9/2/77	50	600	150	dry	-	25.5	512	.318	68.9
9/2/77	51	600	150	dry	-	26.0	499	.318	68.9
9/2/77	52	600	150	dry	-	29.5	502	.318	68.9
9/2/77	53	600	150	dry	-	31.0	503	.318	68.9
9/6/77	54	600	150	dry	-	23.0	497	.318	68.9
9/6/77	55	600	150	dry	-	24.0	498	.318	68.9
9/6/77	56	600	150	dry	-	24.5	498	.318	68.9
9/6/77	57	300	150	dry	-	24.5	497	.318	68.9
9/6/77	58	300	150	dry	-	25.5	499	.318	68.9
9/6/77	59	300	150	dry	-	25.5	499	.318	68.9
9/6/77	60	150	150	dry	-	27.0	498	.318	68.9
9/6/77	61	150	150	dry	-	27.0	500	.318	68.9
9/7/77	62	150	150	dry	-	23.0	497	.318	68.9
9/7/77	63	450	150	dry	-	25.0	511	.318	68.9
9/7/77	64	450	150	dry	-	25.5	499	.318	68.9
9/7/77	65	450	150	dry	-	26.0	500	.318	68.9
9/7/77	66	450	150	dry	-	27.5	500	.318	68.9
9/12/77	67	150	150	wet	water	20.0	496	.318	68.9
9/12/77	68	150	150	wet	water	19.0	493	.318	68.9
9/12/77	69	200	150	wet	water	21.0	496	.318	68.9
9/12/77	70	300	150	wet	water	22.0	496	.318	68.9

Capacitance (uf)	Voltage (v)	Energy (J)	Result
100	100	0.50	Fire in tube @ 5.08-6.35cm above & below electrode followed by rupture of diaphram - over 75% burned
90	100	0.45	Same results as #49, except fire in tube not quite as large... more residue in tube
80	100	0.40	Tube partially filled with flame-diaphram ruptured as before
70	100	0.35	Same basic results as Test #51 above
60	100	0.30	Same basic results as Test #51 above
50	100	0.25	Spark at gap - tube partially filled with flame-diaphram ruptured
40	100	0.20	Spark at gap - no flame
45	100	0.225	Spark at gap - tube partially filled with flame-diaphram ruptured
60	100	0.30	Spark at gap - tube partially filled with flame-diaphram ruptured
50	100	0.25	Spark at gap - no flame
55	100	0.275	Tube partially filled w/flame-diaphram ruptured
100	100	0.50	Spark at gap - no flame
50	400	4.00	Spark at gap - no flame
100	400	8.00	Spark at gap - no flame
50	100	0.25	Fire filled a large portion of tube-diaphram ruptured
40	100	0.20	Fire partially filled tube-diaphram ruptured
30	100	0.15	Spark at gap - no flame
35	100	0.175	Spark at gap - tube partially filled with flame-diaphram ruptured
100	100	0.5	Spark at gap - no flame
100	400	8.0	Spark at gap - no flame
100	400	8.0	Spark at gap - small flame around gap (1.27cm)
100	400	8.0	Spark at gap - small flame along electrode (2.54cm)

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time ms	Spark Gap (cm)	Suspension Pres. kPa	Capaci (u
9/12/77	71	450	150	wet	water	23.0	496	.318	68.9	10
9/13/77	72	150	150	10%	ethy alc	22.5	497	.318	68.9	1
9/14/77	73	150	140	10%	ethy alc	23.0	498	.318	68.9	2
9/14/77	74	150	140	10%	ethy alc	24.0	496	.318	68.9	10
9/14/77	75	300	140	10%	ethy alc	25.5	500	.318	68.9	10
9/14/77	76	300	140	10%	ethy alc	24.0	496	.318	68.9	2
9/14/77	77	300	140	10%	ethy alc	21.5	496	.318	68.9	10
9/14/77	78	450	140	10%	ethy alc	21.0	494	.318	68.9	2
9/14/77	79	450	140	10%	ethy alc	25.5	497	.318	68.9	100
9/14/77	80	150	200	10%	ethy alc	24.0	496	.318	68.9	100
9/14/77	81	150	200	10%	ethy alc	24.0	498	.318	68.9	25
9/14/77	82	150	200	10%	ethy alc	24.0	497	.318	68.9	100
9/15/77	83	450	140	dry	-	24.0	496	.318	68.9	50
9/15/77	84	300	140	dry	-	25.5	498	.318	68.9	100
9/15/77	85	600	140	dry	-	28.0	500	.635	68.9	100
9/15/77	86	600	140	dry	-	29.0	500	.635	68.9	25
9/15/77	87	600	140	dry	-	27.5	500	.635	68.9	100
9/15/77	88	600	140	dry	-	27.5	498	.635	68.9	50
9/15/77	89	300	200	10%	ethy alc	26.0	499	.318	68.9	100
9/15/77	90	300	200	10%	ethy alc	26.0	498	.318	68.9	25
9/15/77	91	300	200	10%	ethy alc	25.5	497	.318	68.9	100
9/16/77	92	450	200	10%	ehty alc	22.0	497	.318	68.9	25
9/16/77	93	150	140	10%	anhy ethr	21.0	496	.318	68.9	100
9/16/77	94	150	140	10%	anhy ethr	22.0	495	.318	68.9	25

citance uf)	Voltage (V)	Energy (J)	Result
100	400	8.0	Spark at gap - small flame around gap (1.27cm)
10	400	0.8	Spark at gap - no flame (.64cm)
25	400	2.00	Spark at gap - small flame around gap (.64cm)
100	400	8.00	Spark at gap - small flame around gap (1.27cm)
100	100	0.50	Spark at gap - small flame around gap (1.27cm) then small running flame along (1) electrode
25	400	2.00	Spark at gap - small flame around gap (1.27cm)
100	400	8.00	Spark at gap - small flame around gap (1.27cm) and along electrode, 2.54cm
25	400	2.00	Spk at gap-sm. flame around gap, 1.27cm & along electrode, 2.54cm
100	400	8.00	Spark at gap - slightly larger flame around gap seemed to be a little brighter
100	100	0.50	Spark at gap - no flame
25	400	2.00	Spark at gap - small 1.27cm lateral flame
100	400	8.00	Spark at gap - small 1.27cm lateral flame
50	100	0.25	Spark at gap - no flame - repeat of 63 - 16 mm @ 64 fps
100	100	0.50	Spark at gap - no flame - above 57-59 series - 16 mm @ 64 fps
100	400	8.00	Spark at gap - flame developed from spark up - 7.62cm then developed from bottom as dust settled - no detonation but diaphram slightly torn, 16 mm
25	400	2.00	Spark at gap - flame filled all of tube then dia. ruptured (bang!) - 16 mm
00	100	0.50	Spark at gap - flame filled all of tube then dia. ruptured (bang!) - 16 mm
50	100	0.25	Spark at gap - no flame
00	100	0.50	Spark at gap - small 1.27cm lateral flame
25	400	2.00	Spark at gap - small 1.27cm lateral flame
00	400	8.00	Spark at gap - small 2.54cm lateral flame
25	400	2.00	Spark at gap - flame streaks from gap up to 5.08cm above
00	100	0.50	Spark at gap - no flame
15	400	2.00	Spark at gap - no flame

2

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time ms	Spark Gap (cm)	Susp Pres.
9/16/77	95	150	140	10%	anhy ethr	23.0	497	.318	68
9/16/77	96	300	140	10%	anhy ethr	24.5	497	.318	68
9/16/77	97	300	140	10%	anhy ethr	24.5	498	.318	68
9/16/77	98	300	140	10%	anhy ethr	25.0	496	.318	68
9/16/77	99	450	140	10%	anhy ethr	24.5	498	.318	68
9/19/77	100	450	140	10%	anhy ethr	22.0	496	.318	68
9/19/77	101	150	200	10%	anhy ethr	22.5	498	.318	68
9/19/77	102	150	200	10%	anhy ethr	22.0	497	.318	68
9/19/77	103	150	200	10%	anhy ethr	22.5	497	.318	68
9/19/77	104	300	200	10%	anhy ethr	24.0	498	.318	68
9/19/77	105	300	200	10%	anhy ethr	23.0	497	.318	68
9/19/77	106	300	200	10%	anhy ethr	23.0	495	.318	68
9/19/77	107	450	200	10%	anhy ethr	24.0	494	.318	68
9/19/77	108	450	200	10%	anhy ethr	24.5	497	.318	68
9/19/77	109	450	140	@ 2 minutes evap. time	ether	25.0	497	.318	68
9/20/77	110	300	140	dry	ether	26.0	500	.318	68
9/20/77	111	300	140	dry	-	27.0	500	.635	68
9/20/77	112	450	140	dry	-	27.0	498	.635	68
9/20/77	113	450	140	dry	-	27.5	501	.635	68
9/20/77	114	-	-	½cc @ 1 mn	ether	27.0	498	.635	68
9/20/77	115	-	-	12 dps @ 1 mn	ether	26.0	498	.635	68
9/20/77	116	-	-	20 dps @ 1 mn	ether	25.5	498	.635	68
9/20/77	117	-	-	15 dps @ 1 mn	ether	25.5	497	.635	68
9/20/77	118	-	-	10 dps @ 1 mn	ether	25.5	496	.635	68
9/20/77	119	-	-	12 dps @ 1 mn	ether	25.5	495	.635	68

ension kPa	Capacitance (uf)	Voltage (v)	Energy (J)	Result
8.9	100	400	8.00	Spark at gap - small flame along spark
8.9	100	100	0.50	Spark at gap - no flame
8.9	25	400	2.00	Spark at gap - small flame along spark
8.9	100	400	8.00	Spark at gap - small flame around gap
8.9	25	400	2.00	Spark at gap - no flame
8.9	100	400	8.00	Spark at gap - small flame along spark
8.9	100	100	0.50	Spark at gap - no flame
8.9	25	400	2.00	Spark at gap - no flame
8.9	100	400	8.00	Spark at gap - small flame along spark
8.9	100	100	0.50	Spark at gap - no flame
8.9	25	400	2.00	Spark at gap - small flame around gap
8.9	100	400	8.00	Spark at gap - small arcing flame along spark
8.9	25	400	2.00	Spark at gap - no flame
8.9	100	400	8.00	Spark at gap - small flame around gap (1.27cm)
8.9	100	400	8.00	Spark at gap - flame filled tube - quick reaction - residual burning
8.9	75	100	0.375	Spark at gap - no flame
8.9	100	100	0.50	Spark at gap - no flame
8.9	100	100	0.50	Spark at gap - no flame
8.9	25	400	2.00	Spark at gap - small flame around gap
8.9	25	400	2.00	Spark at gap - flame filled tube very quickly then loud bang with rupture of dia. (25 drops/¼ cc)
8.9	25	400	2.00	Spark at gap - no flame
8.9	25	400	2.00	Spark at gap - flame filled tube very quickly then loud bang with rupture of dia.
8.9	25	400	2.00	Spark at gap - flame filled tube very quickly then loud bang with rupture of dia.
8.9	25	400	2.00	Spark at gap - very slight reaction above spark (blue flame - (.318cm)
8.9	25	400	2.00	Spark at gap - blue flame filled tube quickly then loud bang with rupture of dia. (sparse flame)

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time ms	Spark Gap (cm)	Suspens Pres. k
9/20/77	120	-	-	10 dps @ 1 mn	ether	25.0	496	.635	68.9
9/20/77	121	450	140	10 dps @ 1 mn	ether	25.0	495	.635	68.9
9/20/77	122	300	140	10 dps @ 1 mn	ether	25.0	495	.635	68.9
9/20/77	123	150	140	10 dps @ 1 mn	ether	25.0	498	.635	68.9
9/20/77	124	150	140	10 dps @ 1 mn	ether	24.5	496	.476	68.9
9/21/77	125	600	140	dry	-	22.0	505	.635	68.9
9/21/77	126	600	140	dry	-	23.0	503	.635	68.9
9/21/77	127	600	140	dry	-	23.0	493	.635	68.9
9/21/77	128	600	140	dry	-	24.0	492	.635	68.9
9/21/77	129	600	140	dry	-	24.0	492	.635	68.9
9/22/77	130	150	140	10 dps @ 1 mn	ether	20.0	490	.318	68.9
9/22/77	131	-	-	10 dps @ 1 mn	ether	21.0	491	.635	68.9
9/22/77	132	-	-	10 dps @ 1 mn	ether	22.0	494	.476	68.9
9/22/77	133	-	-	5 dps @ 1 mn	ether	23.0	496	.476	68.9
9/22/77	134	150	140	5 dps @ 1 mn	ether	24.5	494	.476	68.9
9/22/77	135	-	-	8 dps @ 1 mn	ether	24.5	495	.476	68.9
9/22/77	136	150	140	8 dps @ 1 mn	ether	25.5	496	.476	68.9
9/22/77	137	150	140	8 dps @ 1 mn	ether	24.0	498	.318	68.9

Note: dia. = diaphragm made from lab. filter paper, Grade 615

Suspension Pres. kPa	Capacitance (uf)	Voltage (v)	Energy (J)	Result
68.9	25	400	2.00	Spark at gap - small flame along spark
68.9	25	400	2.00	Spark at gap - flame filled tube quickly then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - flame filled tube quickly then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - flame filled tube quickly then loud bang with rupture of dia.
68.9	100	100	0.50	Spark at gap - flame filled tube quickly then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - flame filled tube then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - flame filled tube then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - flame filled tube then loud bang with rupture of dia.
68.9	50	100	0.25	Spark at gap - no flame
68.9	75	100	0.375	Spark at gap - no flame
68.9	50	100	0.25	Spark at gap - flame filled tube then loud bang with rupture of dia.
68.9	25	400	2.00	Spark at gap - sparse blue flame filled tube quickly then loud bang with rupture of dia.
68.9	100	100	0.50	Spark at gap - small blue flame at gap area; developed late then bang w/rupture of dia.
68.9	100	100	0.50	Spark at gap - no flame
68.9	100	100	0.50	Spark at gap - small 3.72cm flame at & above gap (dia. intact)
68.9	100	100	0.50	Spark at gap - no flame
68.9	100	100	0.50	Spark at gap - flame filled tube then loud bang with rupture of dia.
68.9	50	100	0.25	Spark at gap - 6.35cm flame streak (blue) from gap diagonally up to tube wall; dia. intact

Date	Test No.	Propellent Mass (mg)	Propellent Size No.	Moisture/ Solvent Content	Solution	Temperature °C	Delay Time ms	Spark Gap (cm)	Suspension Pres. kPa
9/22/77	138	-	-	15 dps @ 1 mn	ether	24.0	496	.635	68.9
9/22/77	139	150	140	15 dps @ 1 mn	ether	24.0	499	.635	68.9
9/22/77	140	150	140	10 dps @ 1 mn	ether	24.0	496	.318	68.9
9/22/77	141	450	140	dry	ether	24.5	497	.635	68.9
9/22/77	142	450	140	dry	ether	24.5	495	.635	68.9
9/22/77	143	450	140	dry	ether	25.0	497	.476	68.9
9/23/77	144	300	140	8 dps @ 1 mn	ether	22.0	493	.318	68.9
9/23/77	145	450	140	8 dps @ 1 mn	ether	22.0	497	.318	68.9
9/23/77	146	600	140	8 dps @ 1 mn	ether	24.0	498	.318	68.9

Note: dia. = diaphragm made from lab. filter paper, Grade 615

Lon Pa	Capacitance (uf)	Voltage (v)	Energy (J)	Result
9	25	400	2.00	Spark at gap - flame filled tube very quickly then loud bang w/rupture of dia.
9	25	400	2.00	Spark at gap - flame filled tube very quickly then loud bang w/rupture of dia.
9	25	100	0.125	Spark at gap - flame filled tube very quickly then loud bang w/rupture of dia.
9	25	400	2.00	Spark at gap - flame filled tube then loud pop w/rupture of dia.
9	13	400	1.04	Spark at gap - flame filled tube then loud pop w/rupture of dia.
9	100	100	0.50	Spark at gap - flame filled tube then loud pop w/rupture of dia.
9	40	100	0.20	Spark at gap - flame filled tube quickly then loud bang w/rupture of dia.
9	25	100	0.125	Spark at gap - flame filled tube quickly then loud bang w/rupture of dia.
9	30	100	0.15	Spark at gap - flame filled tube quickly then loud bang w/rupture of dia.

2

APPENDIX B

Use Of The Pressure-Time Trace As Indicator Of Flame Propagation In A Dust Cloud

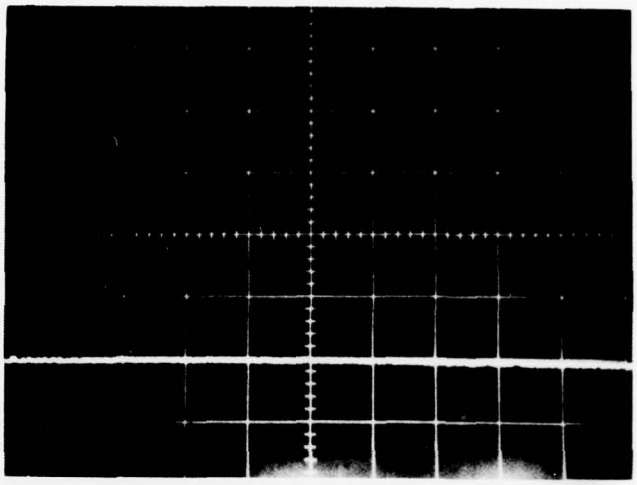
Visual determination of propagation is not the most accurate technique. The last part of the testing program was devoted to the obtaining of pressure traces and attempting to use them along with or in lieu of the present visual propagation criteria. A pressure transducer was mounted about halfway up the lucite tube by drilling a hole into the tube wall. The pressure time trace was recorded and photographed through the use of a biomation unit. A biomation unit is essentially an oscilloscope capable of recording a portion of a trace. The trace begins with the release of air from the air reservoir. It was seen that the release of air from the reservoir does not effect a pressure rise. Later tests had the pressure-time trace begin on the spark, since no significant pressure contribution occurred from the air reservoir. Figure **B-1** shows the pressure traces for Tests 127 and 128. Propagation (the diaphragm burst) occurs in Test 127 while no reaction occurred for Test 128. Tests 127 and 128 are plotted on the explosibility curve of Figure 12 and correspond to filmed Tests 86 and 88, respectively. Note for Test 127 a peak pressure of about 3234.3 kg/m^2 at the instant the diaphragm ruptured.

Figure **B-2** shows the pressure traces of Tests 141-143. All three tests had the same dust concentration, and in all three tests the diaphragm ruptured, thus satisfying the criteria for propagation. Note, however, the difference in the rate of pressure rise in the tests. The rate is highest with the lowest ignition energy.

Unfortunately, no pressure traces were obtained in which propagation nominally occurred (for example, a 10.2 cm flame). The value of the pressure trace would be shown in these nominal cases. However, as stated earlier, the reaction is usually violent (detonation) or minimal (localized flame around gap).

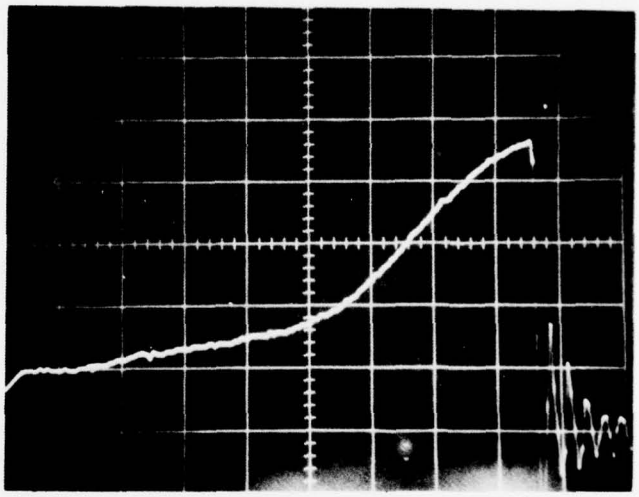
In summary, it can be said that the pressure trace can be used on the Hartmann Apparatus as an aid in determining propagation. Also, its value would be greatest in the tests in which nominal propagation occurs, which was infrequent.

Test No. 128
Spark Energy: 0.25 Joules
No Detonation



Spark

Test No. 127
Spark Energy: 2.0 Joules
Peak Pressure: 31.7 kPa
Maximum Rate of Pressure
Rise: 7.58 kPa/ms
Time From Spark to
Diaphragm Burst: 86 ms
Point A on Figure 12



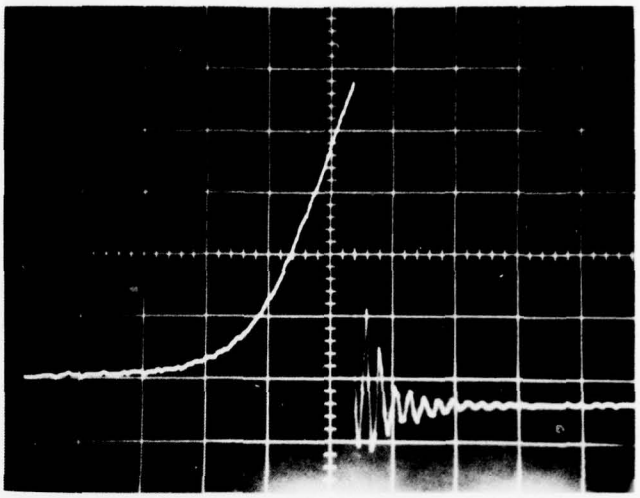
Spark

Diaphragm ↑
Bursts

FIGURE B-1. PRESSURE VERSUS TIME TRACES CORRESPONDING TO FILMED TESTS 86 AND 88 (DRY PROPELLANT IN AIR, CONCENTRATION 0.49 g/ℓ, PARTICLE SIZE 75-105μ).

Test No. 143
Spark Energy: 0.5 Joules
Peak Pressure: 37.9 kPa
Maximum Rate of Pressure
Rise: 882 kPa/msec
Time From Spark to
Diaphragm Burst: 51 msec

Note Scale Same As Figure
13 Pressure Traces.



Test No. 142
Spark Energy: 1.04 Joules
Peak Pressure: 28.3 kPa
Maximum Rate of Pressure
Rise: 965 kPa/msec
Time From Spark to
Diaphragm Burst: 69 msec

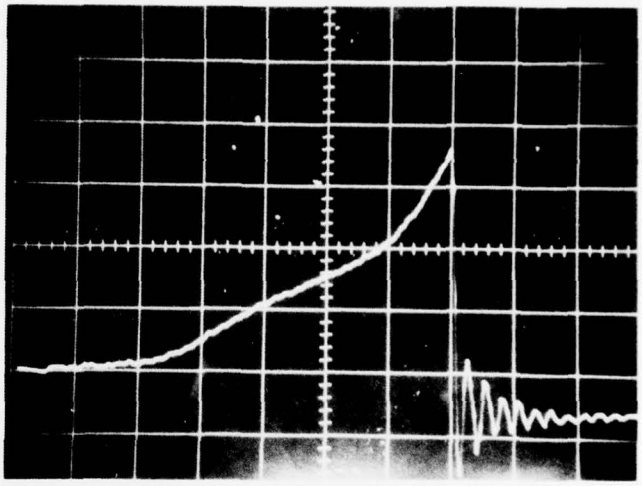


FIGURE B-2. VARIATION OF SPARK ENERGY FOR 0.37 g/ℓ OF DRY PROPELLANT IN AIR (PARTICLE SIZE 75-105μ).

Test No. 141
Spark Energy: 2.0 Joules
Peak Pressure: 25.5 kPa
Maximum Rate of Pressure
Rise: 896 Pa/msec
Time From Spark To
Diaphragm Burst: 81 msec

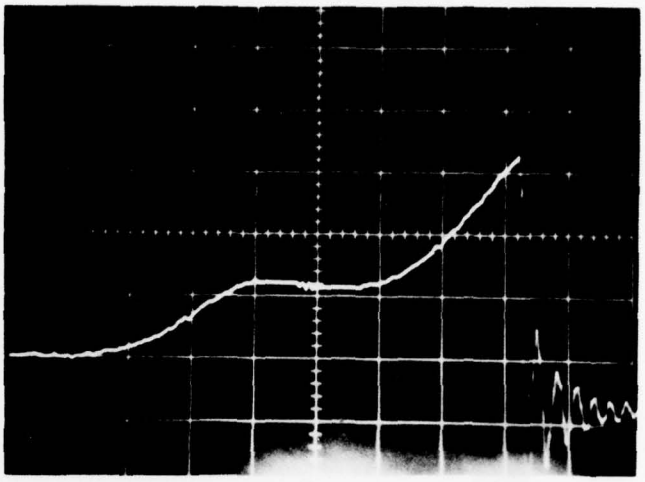


FIGURE B-2. VARIATION OF SPARK ENERGY FOR 0.37 g/ℓ OF DRY PROPELLANT IN AIR (PARTICLE SIZE 75-105μ) (cont'd).

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